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Risø-R-Report

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Risø DTU
National Laboratory for Sustainable Energy

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Abstract (max. 2000 char.):

The programme of the Research Unit of the Fusion Association Euratom - Risø National Laboratory for Sustainable Energy, Technical University of Denmark, covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. Within fusion technology there are activities related to development of high temperature superconductors. Other activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2010.

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Contents

Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in 2019. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry. Risø DTU participates in the internationally coordinated activities to develop fusion and sees itself as having a key role in facilitating the participation of Danish industries in the international fusion programme.

The principle being pursued with ITER is the fusion of hydrogen isotopes to form helium. To make the fusion process run at a significant rate the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. The plasma must be confined to achieve suitable densities and sustain the high temperature. ITER will use a magnetic field for the confinement. While fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, it also presents considerable scientific and engineering challenges. Key issues in the final steps towards realising fusion energy production include:

Improving the plasma energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy. Improving energy confinement implies reducing energy transport out of the plasma, which principally is due to turbulence. Thus, one of the key issues is to understand and control turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

After the merging with the Technical University of Denmark (DTU) in January 2007 Risø has become an institute under DTU with the new name Risø National Laboratory for Sustainable Energy, Technical University of Denmark, in short Risø DTU. As DTU covers many technical and scientific fields of interest for the development of fusion energy, the possibility of expanding the Danish activities in the field are being investigated. Investigations of advanced superconductors operating in high magnetic field are now included in the work plan 2010-2011. Other activities on neutron radiation damages and new material studies are under discussion.

The main contributions from Risø DTU to fusion research in 2010 have been: 1) Models for investigating turbulence and transport are continually improved, and benchmarked against experiments. 2) Central to understanding the dynamics of fast ions is temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. Risø DTU, in collaboration mainly with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson scattering (CTS) diagnostics at the TEXTOR and ASDEX upgrade tokamaks in FZ-Jülich and the Max-Planck Institute for plasma physics in Garching (near Munich).

1 Summary of Research Unit activities

The activities in the Research Unit cover the main areas:

Fusion Plasma Physics, which includes:

- *Theoretical and numerical turbulence studies*. Turbulence and the associated anomalous transport of particles, energy and momentum is investigated using first principles based models and solving these by means of numerical codes in full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at other associations. The activities mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas. The work is performed in collaboration with EFDA partners and in particularly with EFDA/JET.
- *Fast Ion Collective Thomson Scattering.* Risø has taken the lead in the development and exploitation of fast ion collective Thomson scattering diagnostics for TEXTOR, ASDEX Upgrade (AUG) and ITER. These projects are carried out in close collaborations with the TEC† and AUG teams.

Other activities in 2010 have been:

- Investigations of high temperature superconductors for fusion reactors with special emphasis on the characterization of various high temperature superconductor materials.
- Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES.
- Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER.
- Activities on public information about fusion energy. This includes development and presentation of the "Danish Fusion and Plasma Road Show".

The **global indicators** for the Research Unit in 2010 are:

Professional staff:	13.0	man-years
Support staff:	2.7	man-years
Total expenditure - incl. mobility:	2.41	Million Euro
Total Euratom support:	0.53	Million Euro

† TEC: the Trilateral Euregio Cluster, a collaboration of FOM Institute for Plasma Physics, Holland; ERM/KMS, Belgium and Forschungszentrum Jülich, Germany.

2 Plasma Physics and Technology

2.1 Introduction

Plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true for the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. As solid state physics is involved in a broad range of applications, it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at Risø DTU, and gives us access to placing our experimental equipment on large fusion facilities at the Max-Planck Institute for Plasma Physics in Garching and at the Research Centre Jülich, both in Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area.* Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

http://fusion.risoe.dk

Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere × seconds and is currently one atmosphere × seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. This is another of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the TEXTOR tokamak at the Research Centre Jülich and at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, both in Germany.

2.2 Turbulence and transport in fusion plasmas

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the "anomalous" transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore, it is of highest priority to achieve a detailed understanding of anomalous transport and the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

Our activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are strongly involved in the EFDA-JET program; V. Naulin is task force co-leader of Task-Force Transport. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well as defining the ITM data structures. From 2010 A. H. Nielsen is deputy leader for project IMP4. An IMP4 Working Session took place May 3-13, at Risø DTU. We have a significant involvement in the EFDA Topical Groups, and obtained task agreements particularly within the TG Transport and TG MHD, see Sec. 2.2.1. From autumn 2010 V. Naulin is deputy chair for TG Transport.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students.

The work carried out through 2010 included the following items:

- Investigations of filamentary structures related to ELM events including characterization of the so-called Palm Tree Mode, see Sec. 2.2.2, and measurements of the current carried by ELM filaments in the scrape-off-layer, see 2.2.3.
- The involvement in the JET work program is summarized in Sec. 2.2.4. It is focused on areas of transport and MHD.
- Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas by participating in experimental investigations and applying edge/SOL turbulence codes. Turbulence and transport in this region are strongly intermittent and involve outbreaks of hot plasma in the form of density blobs formed near the last closed flux surface (LCFS), and propagating far into the SOL. In Sec. 2.2.5 we investigate the interaction of blob-structures with a sheared flow and Sec. 2.2.6 describes initial results on three dimensional blob evolutions. The influence of finite ion temperature on the evolution of blob structures is investigated numerically in Sec. 2.2.7 by applying a gyro-fluid model, showing a significant effect on the blob dynamics. Finally, Sec. 2.2.9 describes fluctuation measurement in the SOL and Sec. 2.2.10 describes simulations - applying the ESEL code - of the particle density flux as measured by standard probe configurations.
- The development of gyro-kinetic models for the edge/SOL region is discussed in Sec. 2.2.8. The models account for both large electric fields and electromagnetic effects.
- Extensions of transport modeling to two dimensions and by including turbulence spreading effects are described in Sec. 2.2.11 and 2.2.12. These models will be applied to impurity transport and transient transport events.
- In Sec. 2.2.13 we model the influence of edge density fluctuations on electron cyclotron wave beam propagation in tokamaks. The edge density fluctuations are obtained from ESEL simulations.
- Examples of our involvement in the ITM activities are provided in Sec. 2.2.14.

2.2.1 EFDA TG tasks in 2010

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The group has during 2010 participated in the following EFDA TG tasks:

WP10-TRA-05-03: Theory and modeling of edge-SOL turbulence. Comparison between experimental observations and numerical simulations of the turbulence and blob dynamics in the edge and SOL. See, e.g. 2.2.6 – 2.2.10.

WP10-TRA-01-03: Pedestal width physics. Investigation of the influence of transport barrier breakdown, realised by using an empirical ELM model, on the post ELM evolution of the profiles in the presence of turbulence spreading. This task was prolonged till June 30. 2011. Initial results are discussed in Sec. 2.2.5 and 2.2.12.

WP10-TRA-05-01: Currents in filamentary structure inside and outside the LCFS. See 2.2.2 and 2.2.3.

WP10-MHD-03-02: Edge Localised Modes: Magnetic Structures and Current Loss in varying configurations. See 2.2.2 and 2.2.3.

2.2.2 The Palm Tree Mode

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The Palm Tree Mode (PTM) is an ELM post-cursor, which has until now only been detected in JET type-I ELMy H-mode plasmas in situation where the rational $q=3$ surface is in the ELM perturbed region. It has a snake-like signature and a tearing mode structure. Koslowski et al. [1] proposed that the PTM is a remnant of a magnetic island created by edge ergodisation during the ELM, while here we pursue an alternative concept for the explanation of this mode. Our approach is based on the interchange model, which is widely used in Scrape-Off-Layer plasma turbulence. According to this idea, ELMs create positive density perturbations "blobs", which travel radially outwards to be observed as ELM filaments, but also negative perturbations "holes". The latter travels radially inwards and is usually of short lifetime. If such a "hole", a localised perturbation in density and current, is able to reach a resonant surface it closes on itself and increases its lifetime significantly. Figure 1 shows the spreading of the signal around the tokamak along the magnetic field.

The result is a radially and poloidally highly localised filament, which is co-rotating with the ambient edge plasma. This model explains the creation mechanism of the PTM intuitively. The many harmonics observed in the PTM signals are a consequence of the high spatial localisation of the filament. Forward modelling of the magnetic signature of such a filament reproduces the spectra remarkably well.

Empirical mode decomposition (EMD) on MHD and ECE PTM data corroborates our approach. Hilbert amplitude spectra of data from the fast poloidal coil arrays show again that the PTM is a coherent structure. The results prove in an independent way that the higher harmonics as seen in the FFT are a consequence of the high localization of the PTM structure and thus mathematical artefacts.

Finally, the effect of the mode on the temperature measured by ECE is twofold. First it measures the higher temperature inside the filament. Secondly a change in temperature occurs through the change in geometry by the magnetic perturbation of the PTM. These two contributions have been separated for the first time. EMD from a single signal thereby consistently supports the assumption that the PTM is indeed a current filament.

1. H.R. Koslowski et al., Nucl. Fusion **45**, 201 (2005)

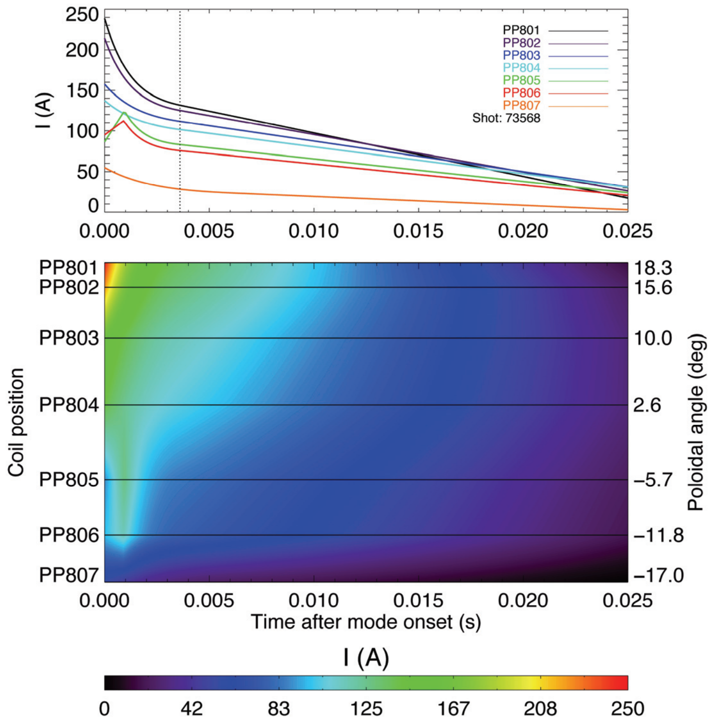

Figure 1: Amplitude envelope of a Palm Tree Mode from measurements, showing initial increase of the amplitude at the inboard side of the tokamak and later resistive decay.

2.2.3 ELM filaments

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Magnetically confined plasmas are often subject to relaxation oscillations accompanied by large transport events. This is particularly the case for the high confinement regime of tokamaks, where these events are termed edge localized modes (ELMs). They result in the temporary breakdown of the high confinement and lead to high power loads on plasma facing components. Present theories of ELM generation rely on a combined effect of edge current and the edge pressure gradients which result in intermediate mode number ($n \cong$ 10-15) structures (filaments) localized in the perpendicular plane and extended along the field line.

It is shown by detailed localized measurements of the magnetic field perturbation associated to an individual type I ELM filament that these filaments carry a substantial current as illustrated in Figure 2 [1].

1. N. Vianello, V. Naulin, R.W. Schrittwieser et al. Phys. Rev. Lett. **106**, 125002 (2011).

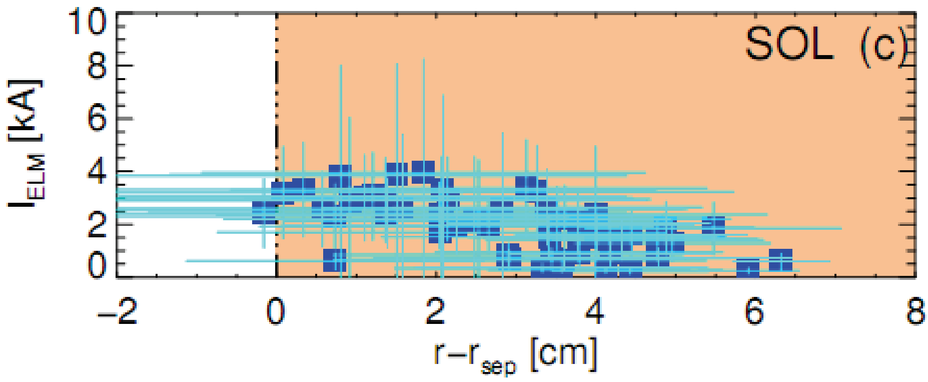

Figure 2. Location of measured filaments in the SOL of ASDEX UG and the inferred current they carry, with error estimates.

2.2.4 JET collaboration

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The activities of and involvement in the JET experimental campaigns focused on the areas of transport and MHD. Investigations of rotation and momentum transport have been performed on JET addressing a couple of important questions on shear flow generation and overall confinement, which is observed to depend on the rotation level. For core confinement investigations are ongoing on how the interplay between q-profile and rotation impacts on the stiffness of the ion temperature profile. A significant effect has been observed at JET, for which as of now no theoretical explanation is available.

The evolution of rotation in the presence of three-dimensional magnetic field perturbations is an important ingredient as three-dimensional effects become increasingly important in tokamak physics due to symmetry breaking perturbations of the magnetic field, for a device previously thought to be completely dominated by its toroidal symmetry. New physics occurring includes rotation breaking by neoclassical toroidal viscosity. This was tested in configurations with error field correction coils and using transport modelling for the analysis. Good agreement between theory and experiment was found [1].

The information obtained from steady state discharges on transport is often limited if not ambiguous and thus open to interpretation. The use of transients with known or unknown sources can provide, time and space resolution of the measurements available, a much improved situation to analyse transport. As a tool torque modulation experiments have been systematically developed and used at JET, for example to verify the existence of a momentum pinch. The methodology and an overview of early results have been reported in [2]. Analysis of transients was also used to determine the impact of ELM losses on the edge rotation and to address the question on how ELMs contribute to the rotation and observed momentum confinement. Results have been published in [3].

1. Y. Sun, Y. Liang, H.R. Koslowski et al., Plasma Phys. Control. Fusion **52**, 105007 (2010).
2. P. Mantica, T. Tala, J.S. Ferreira et al., Phys. Plasmas **17**, 092505 (2010).
3. T.W. Versloot, P.C. de Vries, C. Giroud et al., Plasma Phys. Control. Fusion **52**, 045014 (2010).

2.2.5 Blob shear layer interaction

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At the edge of magnetic confined fusion plasmas, intermittent, large scale transport events (blobs) characterized by high amplitudes of particle density and energy create the plasma profiles in the narrow scrape-off-layer (SOL) between the plasma edge and the plasma limiter/wall. For control of the plasma edge parameters, the dynamic of these intermittent structures has to be fully understood. The prevalent opinion is that the blobs are created in the vicinity of the edge shear layer. Alternatively, it has been suggested that blobs might be created in the density gradient region inside the shear layer itself. The present work investigates the consequences of these presumptions. Thereto the interaction of density and vorticity blobs (Lamb dipoles) with an imposed shear layer is investigated applying the ESEL code [1]. Two different kinds of shear flow implementations are investigated. For the non-consistently frozen shear flow scheme, the potential of the shear flow acts unidirectional at the convective terms of the fields. This ensures a constant shearing profile of the transverse blob structures. Since blobs interact with the shear layer, a consistent implementation was performed by setting up an a-priori defined vorticity distribution and adding a vorticity source term to the ESEL model to keep the vorticity amplitude of the shear layer constant in time.

Figure 3 displays the time evolution of the density of a blob by using the non-consistent shear flow directed in the poloidal (y-) direction and centered in the domain. The shear flow deflects the structure in the poloidal direction. With increasing velocity gradient of the flow, the structure is tilted and rotated. If the vorticity ratio between the shear flow and the structure is sufficiently low, the blob can pass the shear layer. Otherwise the blob is either captured or reflected.

The time evolution of the vorticity of a blob in a self-consistent shear flow is shown in Figure 4. The interchange drive leads to an acceleration of the blob. When the blob reaches the shear layer, the structure is strongly deformed and most of the particles remain at the shear layer, if the vorticity amplitude of the blob is less than that of the shear flow.

1. O.E. Garcia et al., Plasma Phys. Control. Fusion **48**, L1-L10 (2006).

Figure 3. Time evolution of the density of a Lamb dipole in a frozen shear flow. Max. shear rate at the domain center.

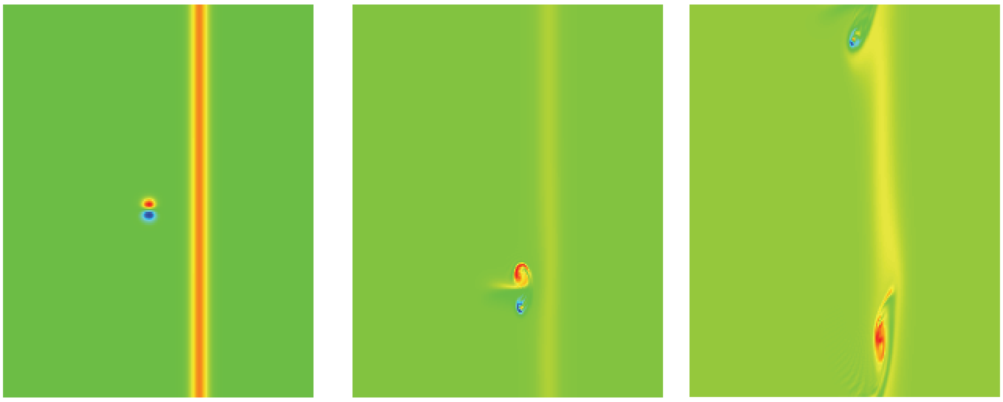

Figure 4. Time evolution of the vorticity of a blob in a consistent shear flow implementation.

2.2.6 Time evolution of blobs in three dimensions

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In magnetic confined fusion plasmas in L-mode, mass, momentum and heat transport from the edge to the scrape-off-layer (SOL) is dominated by intermittent field-aligned filaments, the so-called blobs. These large-scale structures set the power deposition profiles and the structure of the SOL. They ultimately will have to be controlled on ITER to avoid damage to plasma facing components.

In the past, two-dimensional studies of isolated blobs in a geometry perpendicular to the magnetic field were carried out, see e.g. [1]. Also simulations in two-dimensional geometry including blobs and turbulence have been performed [2]. The present work extends these investigations by involving parallel dynamic self-consistently and not only as an effective loss mechanism. This allows an examination of the blob evolution in full three-dimensions. As initial condition, a localised density perturbation superimposed on a uniform background was set up in a cylindrical geometry. In Figure 5, results from initial investigations of the density perturbation in a uniform magnetic field are presented. The parallel extend of the localised structure increases fast at the expense of its amplitude. Since the particles are more mobile parallel to B, the dynamical evolution of the blob is fast in this direction. The localised structure separates symmetrically into two major parts. This initial investigation is performed to test the sheath boundary conditions implemented at the top and bottom of the cylinder. The results from the three-dimensional code will be compared to two-dimensional fluid or kinetic SOL simulations in the future.

The rotation symmetry is broken if we add a perpendicular magnetic field gradient to include curvature effects, where the interchange instability results in radial blob propagation and the occurrence of additional turbulence.

1. O.E. Garcia et al., Phys. Plasmas **13**, 082309 (2006).
2. O.E: Garcia et al., Plasma Phys. and Control. Fusion **48**, L1-L10 (2006).

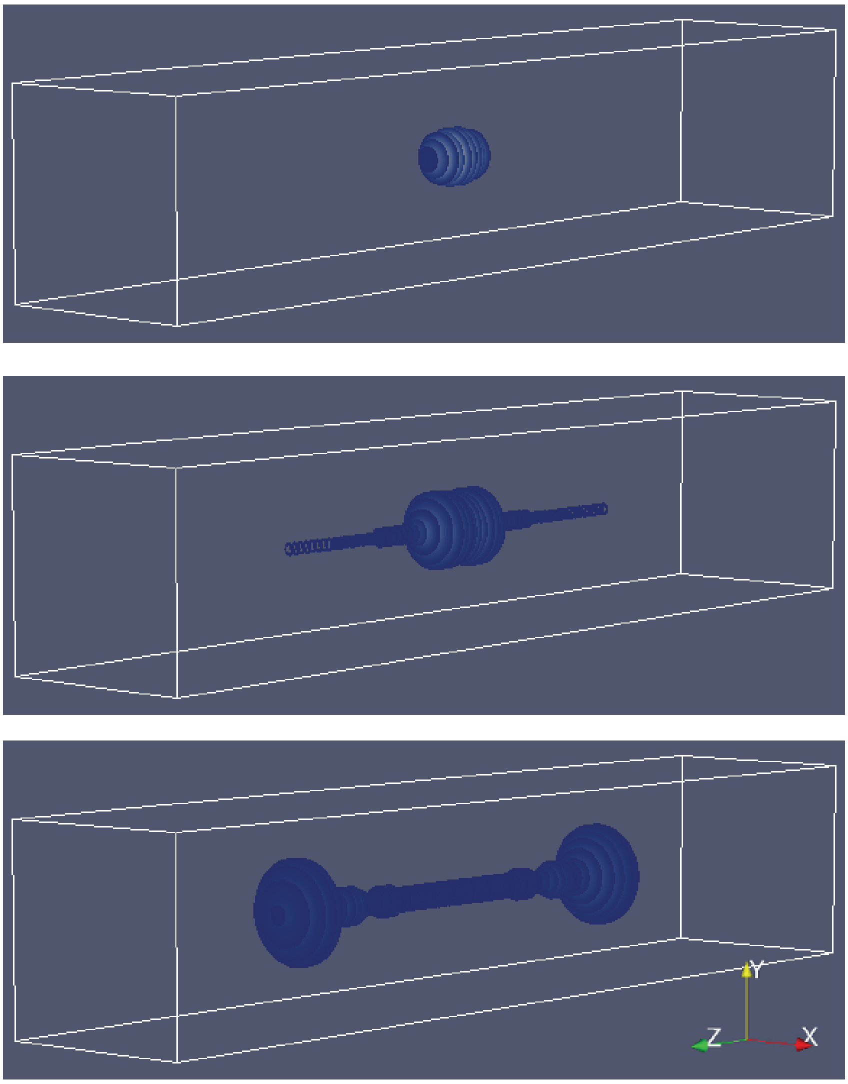

Figure 5. Time evolution of the density of a blob in three-dimensions. The dynamic parallel to the magnetic field, z, is dominating.

2.2.7 Blob convection at finite ion temperature

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Experimental observations have revealed that the transport in the edge and scrape-off-layer (SOL) of toroidally magnetized plasmas is strongly intermittent and involves large outbreaks of hot plasma. These structures, often referred to as "blobs", are formed near the last closed flux surface (LCFS) and propagate far into the SOL. They have a profound influence on the pressure profiles in the SOL, the ensuing parallel flows, and the power deposition on plasma facing components. It is therefore crucial to understand the blob dynamics in order to improve the confinement in present day and future plasma fusion devices, where they are potentially harmful to the plasma facing components.

The blobs have a characteristic spatial size perpendicular to the magnetic field on the order of 1 cm, their radial speeds are up to 10% of the ion acoustic speed, and they have large amplitudes. Edge/SOL temperature measurements report that the ion to electron temperature ratio is 1-10. Measured in units of the ion gyro-radius the characteristic blob size is usually 5-20. Finite Larmor radius (FLR) effects are therefore expected to be of importance for the blob dynamics.

Gyro-fluid models describe full FLR effects and are therefore a natural model choice for investigations of FLR effects on blob propagation. These models are, however, inherently collisionless. Since collisions play an important role in the SOL we added collisional density diffusivity and perpendicular momentum dissipation (viscosity). These ad hoc terms are shown to be energetic consistent and do not generate artificial polarization charge.

A numerical parameter study varying the initial blob size and ion temperature has been carried out. The studies demonstrate that FLR effects have a huge impact on the convection of blobs. First of all the spatial structure is changed and resembles experimental observations. Secondly, the blobs travel faster, further and most importantly carry more energy.

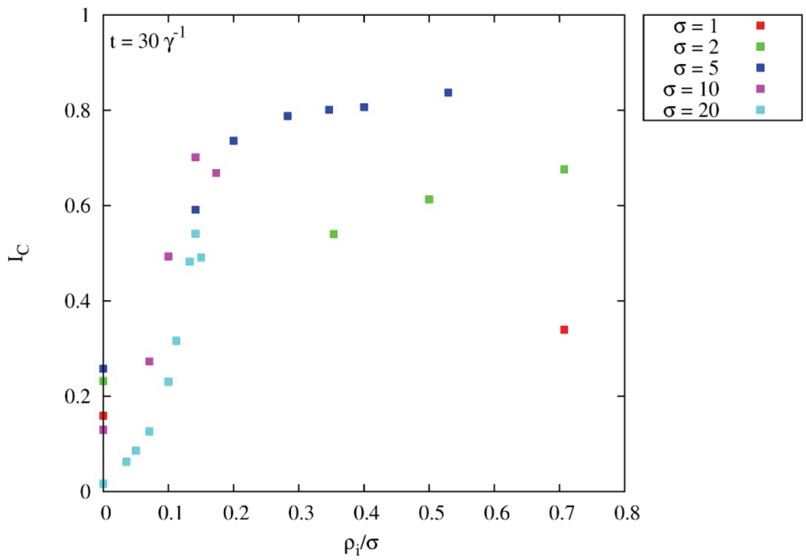

Figure 6. Thermal energy I_C carried by blob after having traveled 15 times the initial blob width. $I_C$is normalized to the initial blob thermal energy.

Figure 6 shows the thermal energy carried by the blob after having traveled its initial width 15 times. $I_C = 1$ and $I_C = 0$ denote blobs having lost none and all initial thermal energy, respectively. Clearly, when the ratio of the ion gyro-radius, ρ_i, to the initial blob size, σ, exceeds approximately 0.1, the carried thermal energy is increasing and reach a value about five times higher.

2.2.8 Edge/SOL gyro-kinetic models

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The development of gyro-kinetic models for the edge/SOL region in toroidal magnetized plasmas is continued and extended [1]. In the edge/SOL region steep gradients are present in the equilibrium profiles and strong shear flows are typically observed in the pedestal and near the edge transport barrier, the relative fluctuation level approaches unity in the SOL and the characteristic length scale of the fluctuations is comparable to the ion gyro-radius. Gyro-kinetic theory utilizes the quasi-symmetry of the gyro orbit to decouple the associated timescale. In the edge and SOL regions the quasi symmetry only exists if the electromagnetic fields are split into high amplitude background and small amplitude perturbed parts. We have for the first time derived explicit Vlasov-Maxwell equations expressed in gyro-kinetic coordinates in the presence of non-stationary background magnetic and electric fields. Also, we have explicitly derived the corresponding local energy theorem. In this model we have identified the polarization charge current (not the polarization drift current) in the Amperes equation, which guarantees polarization charge conservation. The polarization current was neglected in earlier contributions.

1. Association EURATOM-Risø DTU Annual Progress Report 2009, Risø-R-1725, section 2.2.11.

2.2.9 Fast measurements of plasma potential, temperature and density in SOL

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This work focuses on interpretation of fast (1μs) and local (2–4 mm) measurements of plasma density, potential and electron temperature in the edge plasma of the tokamak ASDEX Upgrade. Steady-state radial profiles demonstrate the credibility of the ball-pen probe. It is demonstrated that floating potential fluctuations measured by a Langmuir probe are dominated by plasma electron temperature rather than potential. Spatial and temporal scales are found consistent with expectations based on interchange-driven turbulence. Conditionally averaged signals found for both potential and density are also consistent; however, those for temperature show an unexpected ~4 mm wide decrease by 10% at the very centre of a blob. In the wall shadow, temperature measured by the swept Langmuir probe yields values ~10 eV, whilst the ball-pen temperature gradient is more steep and credible, dropping down to ~1 eV. [1]

1. J. Horacek et al, Nucl. Fusion **50** 105001 (2010).

2.2.10 Numerical simulations of probe signals

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The aim of this work is to simulate the radial particle density flux as observed by a three-probe configuration, using data from ESEL simulations for plasma parameters relevant to JET [1]. The density signal is derived from the ion saturation current to a cold Langmuir probe divided by the square root of the time averaged electron temperature at the probe position. The radial (**E**x**B**) velocity signal is obtained from the potential difference at two probes poloidally separated by a distance Δy. We consider three different kinds of potential probes; cold Langmuir probes, hot emissive probes and ball pen probes, respectively. These probes are considered to be ideal in the sense that they measure an ideal floating potential; $\Phi_{float} = \Phi_{pl} - \alpha T_e$ where α is a parameter that depends strongly on the kind of probe used. Even though we have so far only performed simulations with JET parameters, we believe that the results are relevant also for probes used in other larger tokamaks.

In Figure 7 we display the results of the time average particle flux. To investigate the influence of the potential probes and the ion saturation current, separately, we show two profiles; in the left frame the fluxes are derived using the simulated density, and in the right frame we use the ion saturation current to derive the density. Since we are using the floating potential the derived flux is influenced by a contribution from the electron temperature difference between the positions of the two probes separated by Δy. In the far SOL the spatial scales of the electron temperature fluctuations are larger than the probe separation and the electron temperature difference thus corresponds to the local electron temperature gradient. This gradient is found to be around 90 degrees out of phase with the density, and the temperature variations will thus have limited net contribution to the simulated flux. In the near SOL, we observe temperature fluctuations with length scales comparable to or even smaller than the probe separation. In this case the electron temperature difference does not correspond to the local temperature gradient. This results in a large contribution to the simulated flux as observed.

In the right frame in Figure 7 we observed the same tendency as in the left frame, except that simulated flux profiles have been increased by approximately 50%. The flux, density and electron temperature, are all strongly intermittent and correlated. Therefore, in a flux event the use of a time averaged value of the electron temperature underestimate the electron temperature and thus overestimate the flux.

In both frames are also plotted the flux profile, the blue curves, in the case where we use the density and plasma potential signals and only examine the case of having poloidally separated potential probes. Here, we find fairly good agreement with the "exact" flux (red curve) obtained from the simulations, and thus conclude that a probe separation of Δy=5 mm appears adequate for this choice of ESEL parameters.

1. W. Fundamenski et al Nucl. Fusion **47**, 417 (2007).

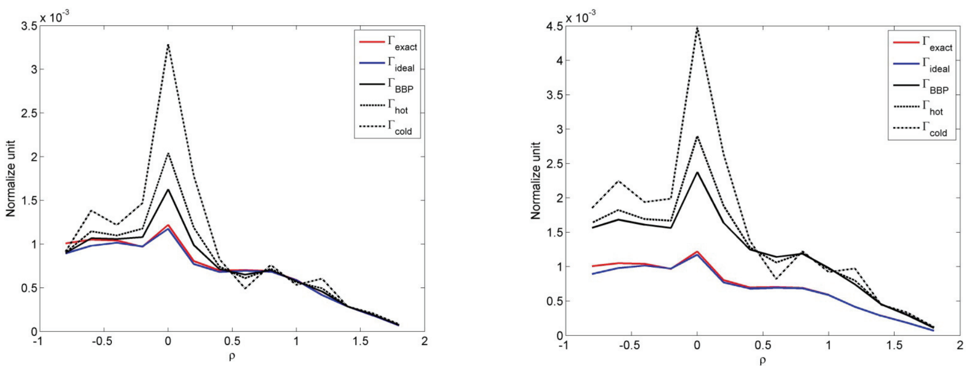

Figure 7. Time average particle flux derived from ESEL simulation using JET parameters [1]. Left frame displays the results using the real plasma density to calculated the fuxes, right frame uses the density obtained from the ion saturation current. Red curves are the exact particle flux, blue curves are for a probe distance of Δy=5 mm and using the plasma potential to derive the radial velocity, and the 3 black curves are using the floating potential from a Ball Pen Probe (α=0.6), hot probe (α=1.15) and cold probe (α=2.8), respectively. ρ=0 is the LCFS.

2.2.11 Two dimensional transport modelling

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Classical transport modelling deals with the fluxes and profiles as functions of the radial plasma coordinate only. Effects such as the ballooning of transport on the outboard midplane and the corresponding poloidal variation of pinch terms are only accounted for in terms of flux surface averaged transport coefficients. In trace Tritium experiments on JET poloidal asymmetries in the trace Tritium density, which lasted for nearly a plasma energy confinement time [1], have supposedly been observed after a localized tracer Tritium injection from the edge. This observation gave rise to look into the consequences of poloidally varying transport coefficients on transient events. A two dimensional transport code based on the ideas of a critical gradient model was thus implemented and tested for various parameters. It was found that poloidal asymmetries in dynamical situations can survive for much longer than anticipated from the large parallel fluxes on a flux surface, see Figure 8. However, for realistic parameters no significant effects on timescales of the energy confinement could be observed, and it was thus concluded that poloidally varying transport coefficients are not explaining the alleged observation of poloidally varying trace Tritium profiles. However, such poloidal effects can have consequences following events localized in space and time, such as ELM bursts and the investigation of these effects will be continued in this direction, including the effects on impurity transport.

1. G. Bonheure, J. Mlynar, A. Murari et al., Nucl. Fusion **49**, 085025 (2009).

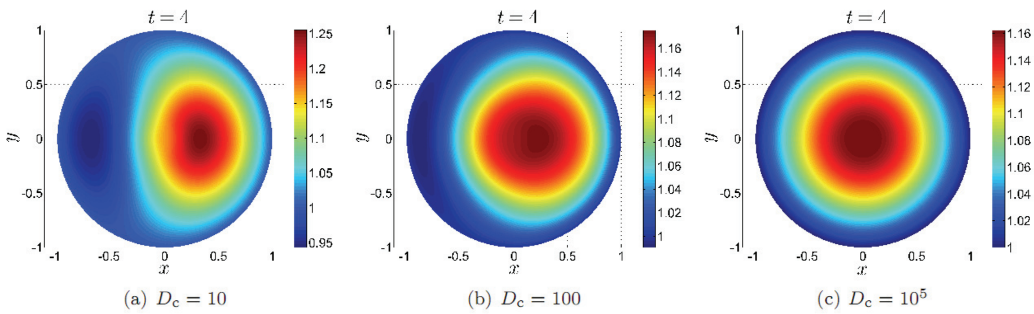

Figure 8. Steady state poloidal assymmetry for various values of the transport on a flux surface, (c) depicting a realistic value.

2.2.12 Turbulence spreading transport modelling

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Anomalous transport is now accepted to be due to turbulence developing from micro-instabilities. Transport modeling assumes local saturation of the turbulence and its associated fluxes. Transport models are therefore put together using local growth rates for the turbulence and saturation space scales. On the other hand, it is well known that the turbulent velocity fluctuations are advecting themselves, so that turbulence created at one spatial location will over time spread out from this location.

The effect of turbulence spreading on transport had been initially investigated with the prospect of explaining disparate transport timescales such as appearing in modulation experiments with flowing cold pulse propagation. A basic transport code had been used and successfully applied for this problem, but difficulties in solving the emerging stiff partial differential equations hindered effective investigations of the parameter space [1].

Here a new code is developed using more adequate methods and potentially, to enhance efficiency, will use advanced parallel methods. Simultaneously it will address turbulence spreading transport and poloidally varying instability rates. The applications will include core impurity transport and transient transport events starting at the edge, for example after ELMs.

1. V. Naulin et al., J. Plasma Fusion Res. SERIES, (2009), **8,** 55-59.

2.2.13 The influence of the edge density fluctuations on electron cyclotron wave beam propagation in tokamaks

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One of the goals of electron cyclotron current drive (ECCD) in tokamak plasmas is the control of magnetohydrodynamic (MHD) instabilities. The effectiveness of this control depends strongly on the achievable localization of the EC driven current density and therefore it is essential to study the various physics effects determining this localization. In this work, we investigate the effects of density fluctuations associated, in particular, with edge turbulence on the EC wave beam propagation as it may affect the beam width and consequent power deposition and ECCD profile. Such effects are expected to be particularly relevant when the beam propagates over a large distance between the fluctuations and the EC resonance layer. This is the case in ITER, in which the distance between scrape-off layer (SOL) density fluctuations and the EC resonance layer is larger than one meter. An immediate consequence of crossing the turbulent edge region will be a perturbation of the phase front of the beam resulting, in turn, in a perturbation of the wave vector spectrum. As the beam propagates, this can result in a broadening of the beam itself.

A numerical analysis of the electron cyclotron (EC) wave beam propagation in the presence of edge density fluctuations by means of a quasi-optical code [1] was performed. The effects of the density fluctuations on the wave beam propagation are estimated in vacuum beam propagation between the edge density layer and the EC resonance absorption layer. Consequences on the EC beam propagation are investigated by using a simplified model in which the density fluctuations are described by a single harmonic oscillation. In addition, quasi-optical calculations are shown by using edge density fluctuations as calculated by two-dimensional ESEL simulations and validated with the experimental data [2]. Typical results are shown in Figure 9 and the detailed results were published in [3].

1. A.A. Balakin et al., Nucl. Fusion **48,** 065003 (2008)
2. O.E. Garcia et al., Nucl. Fusion **47,** 667 (2007)
3. N. Bertelli et al., J. Phys.: Conf. Ser. **260,** 012002 (2010)

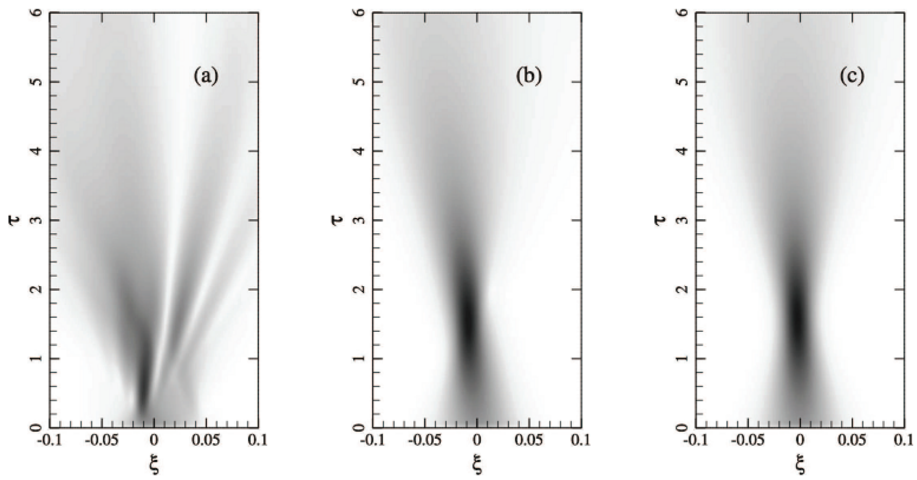

Figure 9. Beam propagation for fluctuation scale length from small to large relative to the width of the beam waist, showing the influence of edge fluctuations (from [3]).

2.2.14 Implementation of CPO/Kepler compatible interfaces into IMP4 codes

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The implementation of technical standards in turbulence codes in the ITM framework (HDF5 data storage, XML parsing of code parameters, MPI implementation for parallel computations and CPO's for inter code data exchange) has been continued in WP10-ITM-IMP4-ACT3-T1. The aim was to design and establish a transparent and versatile IMP4 wrapper routine which – together with comprehensive documentation – allows a quick implementation of turbulence codes on the ITM platform. This has been done by provision of appropriate Makefiles and shell scripts for the platforms in use (GATEWAY and HPC-FF), Quick Reference Manuals and a FORTRAN IMP4-wrapper routine. To proceed towards this goal the already restructured local flux tube code ATTEMPT has been used as a prototype for an IMP4 code. To comply with the different tasks additional FORTRAN codes have been developed, namely the IMP4 wrapper mentioned above and a test bed routine to mimic the envisaged data exchange in the KEPLER framework (FORTRAN work flow). The IMP4 wrapper appears as isolated top piece for the IMP4 code to take care of all UAL specific communication issues, i.e. CPO read/write and XML parsing. By implementation of the ASCII CPO substitutes provided by Ch. Konz it is possible to mimic CPO communication also on HPC-FF (or other platforms) as long as this is not available. The Makefiles and settings of environment variables have been checked and it could be demonstrated that parallel simulation runs within the ITM standards can be realized on GATEWAY and HPC-FF as well. All FORTRAN routines and documentation of this project are available via the ITM repository http://gforge.efda-itm.eu/svn/cpo_interface.

2.3 Diagnosing fusion plasmas by millimetre wave collective Thomson scattering

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Millimetre waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimetre scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to the single megawatt range, CW.

In the world of fusion, millimetre waves are used extensively both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimetre waves, like laser light, can be projected in narrow focused beams, but unlike laser light, the millimetre waves can interact more strongly with the plasma.

At Risø DTU, the millimetre wave collective Thomson scattering (CTS) diagnostic is developed and exploited with two diagnostic aims: for measuring the velocity distribution of confined energetic ions and for measuring the isotope composition (the so-called fuel ion ratio in a D-T fusion reactor) in fusion plasmas. The measurements are spatially localized with a resolution on the centimetre scale and have a temporal resolution on the millisecond scale.

The most energetic (or fastest) ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS). The importance of the fast ion CTS diagnostic was further underlined by the fact that in 2008 the front end of a fast ion CTS diagnostic system was enabled in the new ITER baseline design. In 2009 the updated ITER Baseline Design was finally approved by the ITER Council. Risø DTU has developed the preliminary design of the ITER CTS diagnostic under EFDA task agreements. The work on CTS at TEXTOR and ASDEX Upgrade should be seen in the context of maturing the diagnostic for future use on ITER.

In addition to the use of CTS to diagnose fast ions, the diagnostic technique may also be used to measure the fuel ion ratio in a fusion plasma – both temporally and spatially resolved. This can be done by choosing particular scattering geometries and measure the effect of ion Bernstein waves and ion cyclotron motion on the CTS spectrum (see Section 2.3.3). This novel use of CTS is welcomed by the community since the measurement of the fuel ion ratio in ITER is a challenge with the current diagnostic setup. The CTS based fuel ion ratio diagnostic was investigated and further developed under EFDA tasks under WP08/09 and WP10, and the work of 2010 is further described in Sections 2.3.3 to 2.3.6.

The group has developed and implemented CTS diagnostic systems at the TEXTOR and ASDEX Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. These CTS projects are conducted in collaboration with the TEC[1] consortium and the Max-Planck Institute for Plasma Physics in Garching. Until 2008, the collaboration also included the Plasma Science and Fusion Center at MIT (USA). While they had to withdraw due to financial circumstances, the contact is still maintained.

The upgraded CTS system for TEXTOR was brought into operation in 2005 where the first results were obtained. The operation of the CTS diagnostic was concluded in 2010 as the gyrotron used as a source for the CTS was decommissioned. The considerate continued collaboration effort by our partners (FOM and FZJ) allowed the Risø DTU group to conclude the scientific mission on CTS at TEXTOR during the first part of 2010. An overview of the campaigns and description of the results on TEXTOR is found in Sections 2.3.2 to 2.3.10. In Section 2.3.11 we describe the further development and verification for a technology development for fast data acquisition, which has been crucial for several of the obtained results.

The CTS diagnostic system at ASDEX Upgrade has not been operated in 2010 due to the long shut-down of ASDEX Upgrade for installation of the in-vessel B-coils. However, a large preparatory effort has been made both for operation and hardware upgrades of the CTS diagnostic. An overview of the effort on ASDEX Upgrade is given in Section 2.3.12 and the work is further described in Sections 2.3.13 to 2.3.19.

The activities of the CTS group also involved development of new components, key to the CTS receiver as well as other millimetre wave diagnostics. This work is described in Sections 2.3.20 to 2.3.22.

Visualization of the part of velocity space that the CTS diagnostic system is probing is important when communicating the diagnostic capability and when comparing to other diagnostics. A description of this in the case of ITER is shown in Section 2.3.23. A feasibility study for using CTS for plasma rotation measurements was performed under an EFDA task. The study and conclusions are described in Section 2.3.24.

Finally, a brief description of the group's collaboration with the NIFS CTS group at the Large Helical Device (LHD) is given in Section 2.3.25.

1 TEC: The Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

2.3.1 EFDA tasks in 2010 for the Risø DTU CTS group

S.B. Korsholm, P.K. Michelsen, H. Bindslev, V. Furtula, F. Leipold, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski and M. Stejner
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The CTS group has during 2010 participated in the following EFDA tasks:

- WP10-HCD-01: NBI and LH off-axis current drive efficiency. The work on this is described in Section 2.3.14.
- WP10-DIA-01-01: Measurement of confined alpha particles. Risø DTU took up the task coordination of this task, which is further described in Section 2.3.15.
- WP10-DIA-01-03: Measurements of fuel ratio. Risø DTU continued the task coordination of this task after the WP08/09 task (described in the Association EURATOM-Risø DTU Annual report for 2009). The efforts of Risø DTU on the task are described in Sections 2.3.3 to 2.3.6.
- WP10-MHD-01-03: Sawtooth and Tearing Modes. The work on this task is primarily described in Section 2.3.10.
- WP10-TRA-04-01: Diagnostics for plasma rotation. This task is described in Section 2.3.24.

2.3.2 Overview of results from CTS at TEXTOR

S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, E. Westerhof, A. Bürger***
*(*Association EURATOM-FOM, **Association EURATOM-FZJ)*
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The year 2010 marked the end of a decade long development and utilization of the CTS diagnostic system at TEXTOR. Independently of the work on CTS it had been decided to discontinue and decommission the FOM operated gyrotrons at TEXTOR. This in effect also led to the conclusion of the operation of the CTS diagnostic, which were relying on the 110 GHz gyrotron. However, in order to complete the scientific mission of the CTS diagnostic at TEXTOR the operation of the gyrotron and experimental time for CTS on TEXTOR was kindly prolonged by our collaboration partners of FOM and FZJ.

The experiments of 2010 focused on further development of the diagnostic as a isotope composition diagnostic (Sections 2.3.3 to 2.3.5), and on completing studies of interactions between fast ions and sawteeth (Section 2.3.10), fast ions and RMP (Section 2.3.7), and on particular features in the spectrum related to injection of beam ions (Section 2.3.9). Additionally, a set of velocity distribution functions at different spatial locations and resolved angles have been compared to simulation results in collaboration with VTT and EPFL (Section 2.3.8).

In 2010, the CTS work at TEXTOR has as always been dependent on the continual collaboration with the FOM ECRH team operating the gyrotron source and the FZJ TEXTOR team.

After the successful completion of the experimental campaigns the complete CTS diagnostic system (in- and ex-vessel) has been disassembled and moved to Risø DTU for test and preparation for installation at ASDEX Upgrade 2.3.17.

2.3.3 Plasma composition measurements by CTS: Theoretical work

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Plasma composition measurements by CTS rely on the ability to resolve peaks at frequency intervals roughly corresponding to the ion cyclotron frequencies of the plasma ions which appear in CTS spectra with resolved fluctuation wave vectors near perpendicular. The enhanced sensitivity of spectra containing such features to the ion species mix in the plasma was demonstrated experimentally in proof-of-principle measurements at TEXTOR in 2009 with the help of the newly developed techniques for measurements with high frequency resolution. Such measurements have the potential to form the basis for a new fuel ion ratio diagnostic for burning fusion plasmas. In 2010 our work to develop this new diagnostic principle has progressed through renewed experimental efforts, refined data analysis procedures, a sensitivity study for an ITER fuel ion ratio diagnostic and through detailed analysis of CTS theory to develop a more complete theoretical framework for such measurements.

Specifically, our theoretical work examined the origin of the spectral features which form the basis for measurements of plasma composition by CTS in detail. We found that the enhancement of the sensitivity to plasma composition in CTS spectra with resolved wave vectors near perpendicular to the magnetic field is caused by two separate effects, namely effects of weakly damped ion Bernstein waves on the plasma fluctuation spectrum (as was already well known) and effects of the ion cyclotron motion itself on the driving mechanism for the plasma fluctuations from which the probe radiation is scattered in CTS measurements. It should be noted, that while the effects of the ion cyclotron motion were always included in the codes and in all our theoretical calculations, the importance of this effect had not previously been studied and described in detail.

A detailed study of the principles of fuel ion ratio measurements in fusion plasmas by CTS was recently submitted to PPCF [1]. In this paper the origin and properties of the features created in the CTS spectrum by ion Bernstein waves and the ion cyclotron motion are discussed in detail, and estimates are given of their relative importance for fuel ion ratio measurements.

1. M. Stejner, S. K. Nielsen, H. Bindslev, S. B. Korsholm, and M. Salewski, accepted by PPCF (2011).

2.3.4 Plasma composition measurements by CTS: Experimental work

S.B. Korsholm, M. Stejner, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, S.K. Nielsen, M. Salewski, M. de Baar, A. Bürger**, and the TEXTOR team***
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In 2010 the experimental work on the plasma composition measurements was continued during two campaigns. The experimental techniques were further developed, the available equipment improved, and the increased statistics built up the confidence in the technique. Furthermore, experiments were performed together with the charge exchange recombination spectroscopy (CXRS) group in order to compare the isotope ratio measurements of the two diagnostics – the results of the comparison is still pending.

The ability of the CTS diagnostic to determine the isotope ratio depends critically on having a scattering geometry resolving the dynamics perpendicular to the magnetic field as described in Section 2.3.3. In such geometry the CTS spectrum displays strong particular features with a typical spectral variation in the order of the cyclotron frequencies of the ions in the plasma, i.e. in the order of 20-40 MHz in the case of TEXTOR. The frequency resolution of the fast ion CTS receiver is not that high and thus faster data acquisition techniques are required. We used a Tektronix Digital Phosphor Oscilloscope (model DPO 7104) operating at 5 G samples/s having a bandwidth of 1 GHz for the experiments. This provided us with sufficient frequency resolution. These techniques are described in the 2009 Annual report as well as in Section 2.3.11.

To illustrate the sensitivity of the diagnostic method to the scattering geometry we performed an experiment, where the probing and receiving mirrors were swept toroidally in parallel while maintaining overlap. This enabled the acquisition of a series of spectra having different resolved angles to the magnetic field. In Figure 10 we present the result of the experiment with a series of 7 spectra having resolved angles in the range 85° to 95°. It is clear that the cyclotron frequency related features in the spectrum are more prominent near 90°, while they disappear when the geometry is no longer near perpendicular.

The results of the first measurements of intrinsic ion Bernstein waves was submitted and recently accepted for publication in Physical Review Letters [1].

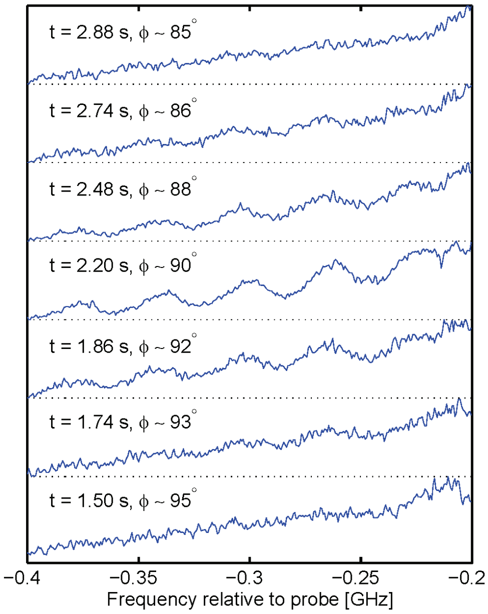

Figure 10. Measured CTS spectra for seven representative angles around $\phi \sim 90°$ made during a sweep of the probing and receiving mirrors during TEXTOR discharge #111796. The spacing between the peaks is 40 MHz, corresponding to ω_{cH} at the location of the scattering volume. The respective time and approximate ϕ are indicated in each graph. The ϕ -values are obtained by ray tracing.

1. S. B. Korsholm, M. Stejner, H. Bindslev et al, *Measurements of intrinsic ion Bernstein waves in a tokamak by collective Thomson scattering*, Accepted for publication in PRL (2011)

2.3.5 Plasma composition measurements by CTS: Data analysis

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In 2010, we have worked to further expand and refine the software tools used for raw data analysis of CTS spectra with high frequency resolution and for detailed interpretation of the features created in the spectra by ion Bernstein waves and ion cyclotron motion. The analysis codes have been expanded to account for the effects of drift in the probing frequency (due to thermal expansion of the gyrotron cavity), and to fully exploit the new gating technique for the oscilloscope allowing measurements to be conducted throughout a plasma discharge (see Section 2.3.11). The fitting routines used to infer plasma parameters from the measured spectra were refined for greater reliability and accuracy, a new and faster method for optimization of the fits based a genetic algorithm was developed, and the CTS model fitted to the measured spectra was adapted to include the effects of ion species with different temperatures. In addition, development of a parallelized version of the codes building on the Fortran Message Passing Interface was initiated to exploit the large Linux clusters available at Risø DTU for post discharge analysis. This will significantly speed up the data analysis which can be highly CPU demanding, and it is a prerequisite for analysis of the large number of spectra resulting from the new gating technique.

Figure 11 shows an example of results from the analysis of data spanning at time window 1.9 s and taken with the new gating technique in TEXTOR discharge 111815. In this discharge the position of the CTS measurement volume was moved from the center to the low field side (R=1.78 m to 2.12 m). The CTS spectra, and in particular the features created by ion Bernstein waves and ion cyclotron motion, change consistently with the decreasing density, temperature and magnetic field strength as the measurement volume moves outwards. By fitting the spectra, and under the assumption of steady state conditions, we expect to get a radial profile of the plasma composition. Figure 12 shows the inferred plasma composition in the center of TEXTOR discharge 111827 in a 40 ms wide time window. In this discharge the plasma composition was also measured by charge exchange recombination spectroscopy, and a comparison of the results is underway.

Results from analysis of proof-of-principle experiments demonstrating the sensitivity of CTS spectra to plasma composition were submitted to PRL in 2010 [1]. Results of detailed data analysis to infer the plasma composition from measured spectra will be submitted very soon (currently on pinboards) [2].

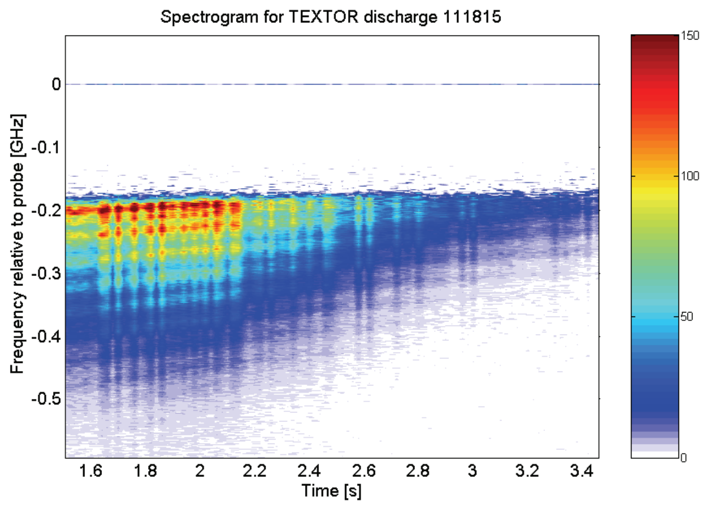

Figure 11. The spectrogram obtained from the oscilloscope in TEXTOR discharge 11115. The receiver beam was swept along the probing beam whereby the measurement volume was moved from the center to the low field side. The CTS spectra changes consistently with the decreasing density, temperature and magnetic field strength as the measurement volume moves outwards.

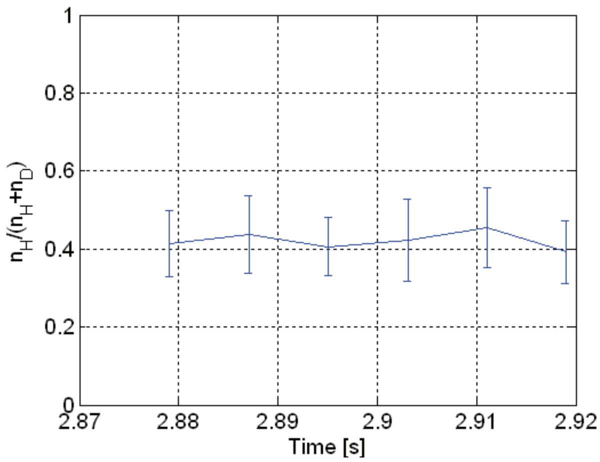

Figure 12. Results of data analysis from TEXTOR discharge 111827. The graph shows the hydrogen to deuterium density fraction, $R_H=n_H/(n_H+n_D)$, inferred from the measured spectra. The gating technique was not used and the time window is therefore limited to 50 ms. Results for this discharge will be compared to measurements by CXRS.

1. S.B. Korsholm, M. Stejner, H. Bindslev et al, *Measurements of intrinsic ion Bernstein waves in a tokamak by collective Thomson scattering*, Accepted for publication in PRL (2011)
2. M. Stejner, S.B. Korsholm, S.K. Nielsen, et al, to be submitted to PPCF (2011).

2.3.6 Plasma composition measurements by CTS: Sensitivity study for ITER

M. Stejner, S.B. Korsholm, S.K. Nielsen, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, M. Salewski
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Supplementary to experimental efforts to demonstrate the ability of CTS to diagnose plasma composition in current machines we have performed a detailed sensitivity study to investigate the potential accuracy of fuel ion ratio measurements in ITER. Results from this study will be part of the scientific report for EFDA contract WP10-DIA-01-03 which will give a comparison of the expected accuracies of fuel ion ratio measurements in ITER for a range of diagnostics techniques. This work was therefore coordinated with parallel work on neutron spectroscopy by ENEA-CNR and Uppsala University, neutron radiometry by ENEA Frascati, and on charge exchange recombination spectroscopy by FOM.

In the sensitivity study we assume plasma parameters (density, temperature etc.) corresponding to results from the ASTRA simulation code [1] for a 15 MA inductive scenario – *Scenario 2*. Taking these plasma parameters as our starting point we calculate the expected relative accuracy, σ_{Ri}/R_i with $R_i=n_T/n_D$, of fuel ion ratio measurements by CTS within the framework of the Bayesian least squares method of inference frequently used to interpret CTS data [2]. The Bayesian approach allows the calculations to include information about the accuracy of other diagnostics at ITER measuring parameters (e.g. the electron density and temperature) which influence the CTS spectrum, but which are of secondary interest for the purpose of fuel ion ratio measurements. For such *nuisance parameters* we assume that they can be measured by other diagnostics with the accuracies given in the ITER diagnostics database, Chapter 7 of the ITER physics basis [3], and those measurements can be used as input for the interpretation of the CTS spectra.

Figure 13 shows an example of results from the sensitivity study. The figure shows a contour plot of the expected relative accuracy, σ_{Ri}/R_i with $R_i=n_T/n_D$, of fuel ion ratio measurements by CTS in the core of ITER for a scan of plasma composition, R_i, and temperature with all other parameters fixed. The temperature is varied by scaling the ion and electron temperatures by a common factor (the 'temperature scaling factor' on the ordinate). The results indicate that for the conditions predicted by the ASTRA simulation (along the horizontal line corresponding to 1 on the ordinate) the fuel ion ratio can be measured with a relative accuracy of 10 % for R_i ranging from 0.01 to 30. For lower temperatures the accuracy is higher and the range of R_i where acceptable accuracy can be achieved is wider – and vice versa for higher temperatures. This result is general in the sense that the highest accuracies are achieved for roughly equal deuterium and tritium densities while variations in other plasma and system parameters mainly lead to widening or narrowing of the range of R_i where acceptable accuracy can be achieved – with only the most extreme conditions leading to a complete loss of ability to diagnose the fuel ion ratio.

From results from the sensitivity study it may therefore be expected that a CTS fuel ion ratio diagnostic would be able to meet the diagnostic requirements for ITER under most of the relevant plasma scenarios. A more detailed overview of the results will be part of the scientific report for EFDA contract WP10-DIA-01-03, and the results are further planned for publication in 2011.

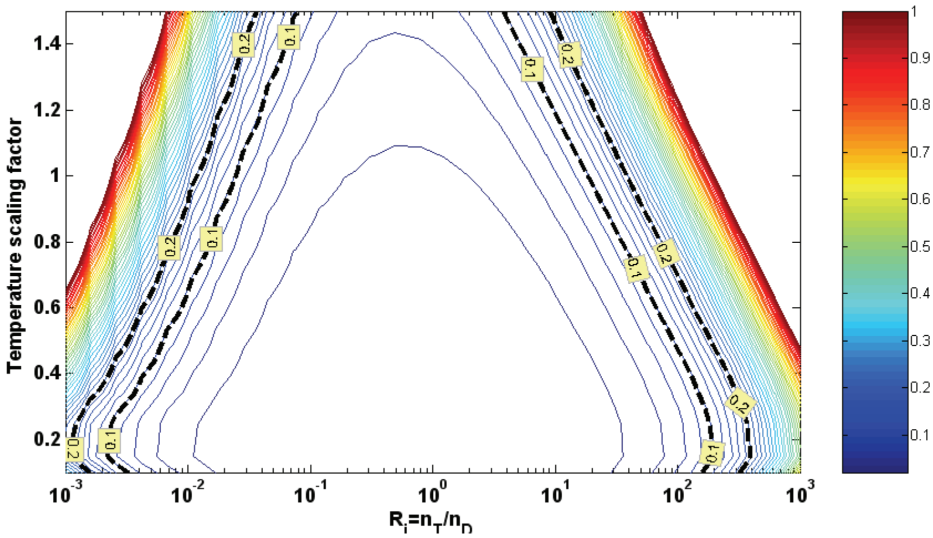

Figure 13 Example of results from the sensitivity study for a CTS fuel ion ratio diagnostic on ITER. The figure shows 50 linearly spaces contours for the expected relative accuracy, σ_{Ri}/R_i, with which R_i can be measured for a scan of R_i and temperature. The calculations assume plasma parameters from the ASTRA simulation code for a 15 MA inductive scenario (Scenario 2) and uncertainties of input from other diagnostics corresponding to the accuracies listed in the ITER physics basis. The temperature is scanned by scaling the electron and ion temperature by a common factor so conditions in the ASTRA simulation results correspond to 1 on the ordinate. The thick dashed lines show the regions within which relative accuracies of 10 and 20 % can be achieved, respectively.

1. A R Polevoi, M Shimada, and V S Mukhovatov, Plasma Physics and Controlled Fusion **48**, A449-A455 (2006).
2. H. Bindslev, Review of Scientific Instruments **70**, 1093 (1999).
3. A. J. H. Donné, A. E. Costley, R. Barnsley, et al, Nuclear Fusion **47**, S337-S384 (2007).

2.3.7 Collective Thomson scattering experiments in TEXTOR with resonant magnetic perturbations

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TEXTOR is equipped with the dynamic ergodic divertor (DED). It is a set of external coils which can create resonant magnetic perturbations (RMP) with various mode numbers, both static and rotating. We attempted to investigate the possible influence of RMP on the confinement of fast ions by means of the collective Thomson scattering (CTS) diagnostic.

The DED was configured to produce RMP in (m, n) = (6, 2) DC mode. The fast ion measurements were conducted in the plasma center (see Figure 14) in the direction close to parallel to the magnetic field. The experiments were designed to measure the fast ion slow-down time. By this we aimed to neglect the influence of changes in the ionization profile of the beam ions due to changes in the density profile invoked by the RMP. The DED operation in TEXTOR requires ctr-Ip NBI for stability reasons and it is known to be a cause features in the CTS spectrum which makes data analysis difficult. However, interesting data were obtained from discharge 111826. In this discharge, the maximum possible DED current was not sufficient for the stochastic region to reach the so-called pump-out regime observed when the stochastic region overlaps the resonant surface. However, the enhanced particle confinement regime caused by DED was observed. Observation of this phenomenon in TEXTOR has been reported earlier [1]. In another discharge the DED operation triggered the formation of the (m, n) = (2, 1) locked mode (Figure 15) which unlocked after the DED was switched off. Hence, future analysis will help to reveal new aspects of the fast ion confinement with and without magnetic islands present. The CTS data analysis for other discharges in the RMP campaign is still ongoing.

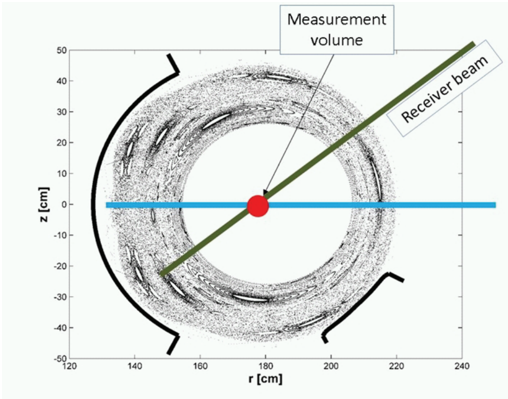

Figure 14. CTS measurements in presence of RMP: Location of the measurement volume.

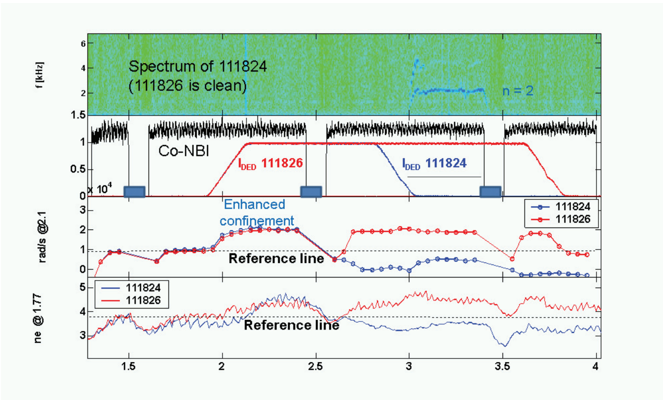

Figure 15. CTS measurements in presence of RMP: Time traces of experimental data for discharges 111824 and 111826. The blue boxes depict the CTS measurement periods. The upper graph shows the magnetic spectrogram of 111824; the second subplot shows the timing of the co-Ip NBI and the DED; the third subplot show the plasma rotation frequency measured by CXRS; the bottom graph represents line integrated density measured by the interferometer.

1. O. Schmitz, J.W. Coenen, H. Frerichs, M. Kantor, M. Lehnen, B. Unterberg, S. Brezinsek, M. Clever, T. Evans, K.H. Finken, M. Jakubowski, A. Kraemer-Flecken, V. Phillips, D. Reiter, U. Samm, G.W. Spakman, G. Telesca and the TEXTOR team, Journal of Nuclear Materials 390–391, 330–334 (2009)

2.3.8 Comparison of the fast ion velocity distribution function by CTS in TEXTOR and calculated by the ASCOT and VENUS codes

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Comparison of measured fast ion velocity distribution functions with numerical codes is important. The CTS diagnostic enables measuring 1D projection of the fast ion velocity distribution function g(u), on a direction determined by the probe and receiver antennae settings. The measurements were made in four discharges at different radial positions and resolved angles ϕ, relative to the magnetic field. The measurements were made at the plasma center and off-axis for two different resolved angles ϕ. Hydrogen neutral beam injection (NBI) was used as a source of fast ions. During the measurements sawtooth activity was observed, while no other MHD activity was detected by the Mirnov coils and the soft X-ray diagnostic.

For the comparison between measurements and codes the fast ion velocity distribution function measured at the end of the sawtooth period was chosen in order to avoid the effect of fast ion redistribution due to sawteeth (see Section 2.3.10). The ASCOT (Aalto University, Finland) [1, 2] and VENUS (EPFL, Switzerland) [3] codes were used to simulate the fast ion distribution function in the experiment. In the simulations a static plasma background was assumed and the codes did not include the effects of any anomalous mechanisms of fast ion transport.

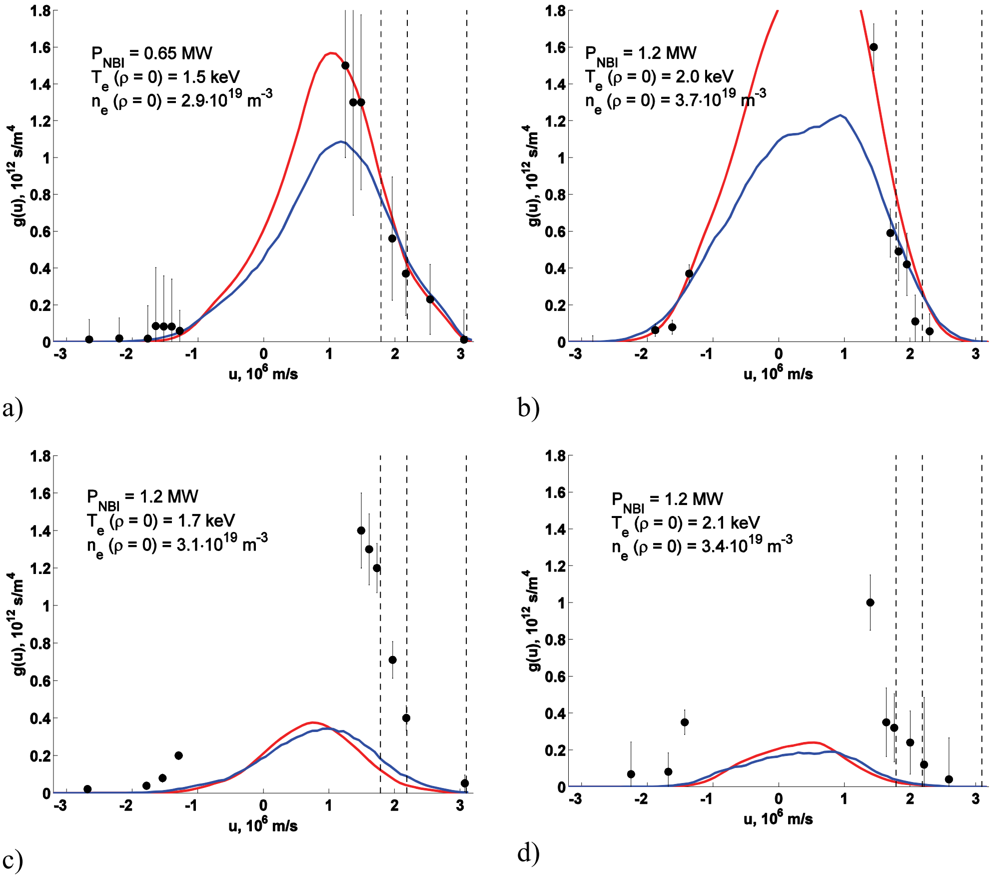

Figure 16. g(u) for the measurements at different radial positions and ϕ angles. Black dots with error bars correspond to experimental distribution function; solid red and blue lines - simulated, ASCOT and VENUS respectively; black dashed lines show the velocities corresponding to E, E/2 and E/3 beam energy fractions, the error bars correspond to one standard deviation. (a) Discharge 111822, ϕ = 138°, R = 1.84 m; (b) Discharge 111506, ϕ = 107°, R = 1.79 m; (c) Discharge 111509, ϕ = 127°, R = 2.0 m. Error bars for negative velocities are hidden by markers; (d) Discharge 111512, ϕ = 106°, R = 1.97 m.

The results of the comparison are presented in Figure 16. The good agreement in the center allows us to posit that the fast ion distribution function in the center of TEXTOR can be described with no anomalous transport mechanisms. For the off-axis scenarios a qualitative agreement is observed. Discrepancies between the experiment and modeling can be partly explained by experimental uncertainties and the assumptions used for the simulations.

1. J.A. Heikkinen and S.K. Sipila, Physics of Plasmas, **2**, 3724 (1995)
2. T. Kurki-Suonio, O. Asunta, T. Hellsten, V. Hynönen, T. Johnson, T. Koskela, J. Lönnroth, V. Parail, M. Roccella, G. Saibene, A. Salmi and S. Sipilä Nuclear Fusion, **49**, 095001 (2009)
3. O. Fischer, W.A. Cooper, M.Y. Isaev and L. Villard Nuclear Fusion, **42**, 817–826 (2002)

2.3.9 Ion cyclotron emission from NBI heated TEXTOR plasma

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During experiments with counter-I_p and radial neutral beam injection in TEXTOR the CTS spectrum was found to contain ion cyclotron harmonic structure. In order to perform the experiments, the CTS receiver was upgraded to allow analysis of the data with very high frequency resolution (see Section 2.3.11). We found that emission in the ion cyclotron range of frequencies was triggered by the counter-I_p Hydrogen NBI and the radial diagnostic neutral beam injector (RUDI). The co-I_p NBI was found to have a stabilizing effect on the wave excitation.

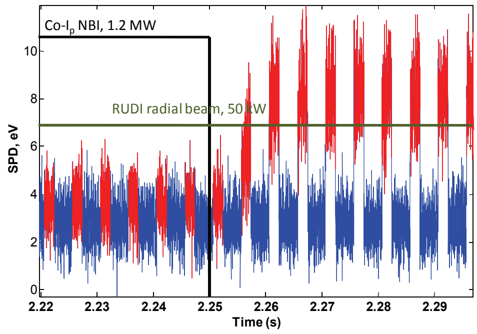

Figure 17. Spectral power density in the CTS receiver channel which was sensitive to the observed effect; Red: probe-on periods; Blue: probe-off periods.

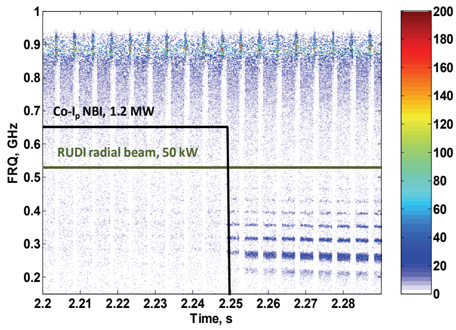

Figure 18 Spectrogram of the CTS data. The probing frequency in this figure corresponds to the frequency of around 1.05 GHz.

Figure 17 and Figure 18 show an example of the instability excited by the RUDI beam. The RUDI beam was switched on at 2.2 s, the co-Ip NBI was also on during that time and no effect in the CTS signal was observed. However, when the co-Ip NBI was turned off at 2.25 s the signal associated with the RUDI beam started to emerge (see Figure 17). The spectrogram with a spectral resolution of 0.5 MHz depicted in Figure 18 shows that the signal consists of multiple peaks separated by the frequency approximately equal to the ion cyclotron frequency of hydrogen in the plasma center (see Figure 19). The peaks are drifting with time.

In Ref. 1 the observation and explanation of similar results from TFTR is presented. It states that the instability could be triggered by the population of fast ions with very narrow velocity spread.

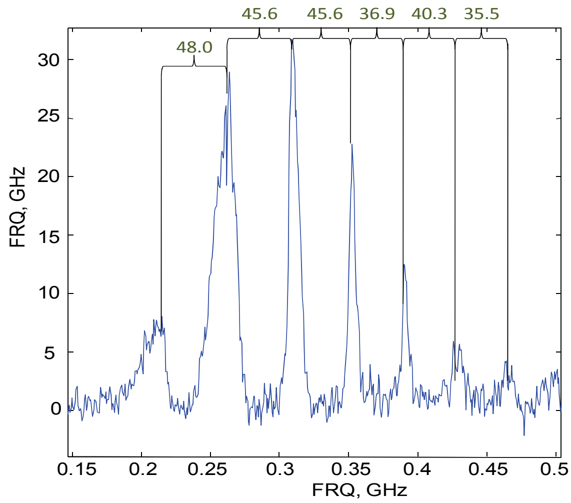

Figure 19. A time slice of the spectrogram presented in Figure 17 at 2.28 s. The probing frequency in this graph corresponds to approximately 1.05 GHz.

1. R.O Dendy, K.G McClements, C.N Lashmore-Davies, G.A Cottrell, R Majeski, and S Cauffman, Nuclear Fusion 35, 1733-1742 (1995)

2.3.10 Collective Thomson scattering measurements of fast ion redistribution due to sawteeth

*S.K. Nielsen, M. Salewski, H. Bindslev, A. Bürger**, E. Delabie*, V. Furtula, M. Kantor*, S.B. Korsholm, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, J.W. Oosterbeek*, M. Stejner, E. Westerhof*, P.P. Woskov***, and the TEXTOR team** (*Association EURATOM-FOM, **Association EURATOM-FZJ, ***PFSC MIT, USA)*
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Fast-ion CTS measurements in neutral beam injection (NBI) heated TEXTOR plasmas with sawtooth oscillations have been reported [1, 2]. The measured 1D fast-ion distribution was found to drop up to 50% for resolved directions with a significant component parallel to the magnetic field due to a sawtooth crash.

In Figure 20 measured central velocity distributions prior to and after a sawtooth crash are shown with a resolved angle of 110° to the background magnetic field. The crash reduces the non-thermal fast-ion population between u = 0.8 10^6 m/s and u = 1.6 10^6 m/s significantly. The bulk ion distribution is included in the plot as a reference. At negative velocities the projected fast-ion velocity distribution function, g(u), does not drop at the time of the sawtooth crash. Since the TEXTOR NBI fast-ion distribution function is anisotropic, the measured g(u) for positive and negative projected velocities might be different since they sample different parts of the 2D velocity space.

Figure 21 shows a fast-ion distribution function, $f(v_\parallel,v_\perp)$, obtained from a basic Fokker-Planck model for a homogeneous plasma. On TEXTOR the plasma current is directed opposite to the magnetic field which implies that ions with negative $v_\parallel$ travel in the direction of the plasma current. The parts of $f(v_\parallel,v_\perp)$contributing most to the projected velocity distribution function, g(u,t), for four particular velocities at a resolved angle of 110° are also plotted. The contributions to g(u) with positive velocities (u = 1.3 10^6 m/s and u = 1.9 10^6 m/s) are dominated by passing ions with $|v_\parallel|>|v_\perp|$ while the contributions with negative velocities (u = -1.3 10^6 m/s and u = -1.9 10^6 m/s) include significant numbers of trapped ions with $|v_\parallel|<<|v_\perp|$.

This demonstrates that the co-passing fast ions react differently to a sawtooth crash compared with the trapped particles.

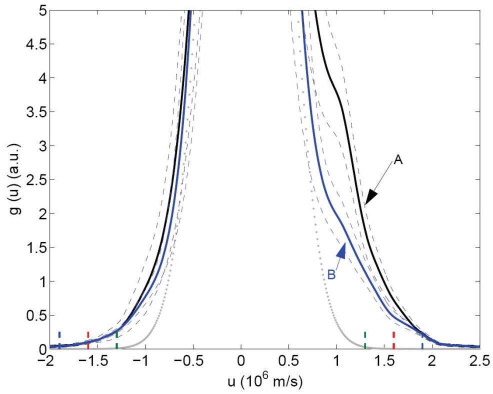

Figure 20. Ion velocity distribution just before (A) and after (B) a sawtooth crash. The error bar limits are represented by dashed lines. The bulk ion distribution (dotted line) is shown for reference.

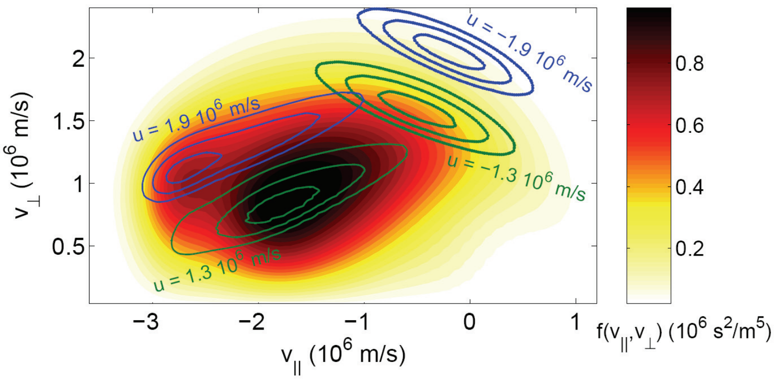

Figure 21. Filled contours show the central TEXTOR hydrogen beam ion velocity distribution calculated with a Fokker-Planck solver for a homogenous plasma. The closed lines show the regions in velocity space which contribute most to g(u) for the calculated distribution function (see Section 2.3.23).

1. S. K. Nielsen et al, Plasma Phys. Control. Fusion **52** 092001 (2010)
2. S. K. Nielsen et al, submitted to Nuclear Fusion (2011)

2.3.11 Development and verification of acquisition technique for CTS measurements with high frequency resolution

M. Stejner, S.K. Nielsen, S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, M. Salewski
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During 2010, the development of acquisition techniques for CTS measurements with high frequency resolution was continued and results were compared against theoretical predictions and measurements with the standard acquisition technique. In the standard acquisition technique the signal is split into several band pass limited channels, the bandwidth of which defines the frequency resolution of the measurement. The power level in each channel is then measured by ADCs with 24 bit resolution. This provides a highly sensitive acquisition over a very large dynamic range but with relatively poor frequency resolution – typically the channel band width is around 80-100 MHz. For measurements with high frequency resolution a portion of the central part of the spectrum is down-converted to a frequency range between 0.1 GHz and 1.1 GHz using a second heterodyne mixing stage. The down-converted signal is then recorded using a Tektronix Digital Phosphor Oscilloscope (model DPO 7104) operating at 5 G samples/s. To obtain the spectral power density, the recorded signal is Fourier transformed and calibrated with the total instrument function. The central part of the spectrum can thus be resolved with a frequency resolution better than 1 MHz over a 1 GHz wide frequency interval. This technique permits very detailed investigation of the CTS spectrum, it is a necessary prerequisite for measurements of plasma composition by CTS, and it may further permit very accurate measurements of bulk ion temperatures by CTS. In addition it enabled detailed studies of cyclotron structures in CTS spectra during certain NBI heating scenarios at TEXTOR which are believed to be related to NBI induced instabilities near the plasma edge (see Section 2.3.9). The technique further enabled the characterization of secondary emissions from ICRH on AUG.

During 2010 the technique was further developed. Effects of standing waves in the set-up were minimized, efficient data analysis techniques and procedures for obtaining calibration functions were developed, acquisition with an oscilloscope with a larger bandwidth was successfully tested and, perhaps most importantly, a new gating technique for the oscilloscope was developed to permit measurements throughout a plasma discharge. Due to memory constraints of the oscilloscope, it was previously only possible to obtain measurements in a single 50 ms time window for each plasma discharge. Using the new gating technique, it is now possible to economize the available memory for measurements throughout a discharge by letting each gyrotron pulse trigger a brief (0.5 ms) measurement with the oscilloscope. Figure 22 shows an example of such a measurement from a discharge in which the receiver beam was swept past the probing beam producing a transient overlap between the two beams. To benchmark the data obtained with high frequency resolution the spectra were compared to theoretical predictions and to simultaneously measured spectra from the standard receiver. The high-resolution spectra are consistent with both the theoretical predictions and the standard spectra. Figure 23 shows and example of such a comparison.

A detailed technical description of the acquisition technique for CTS measurements with high frequency resolution was published during 2010 in [1]

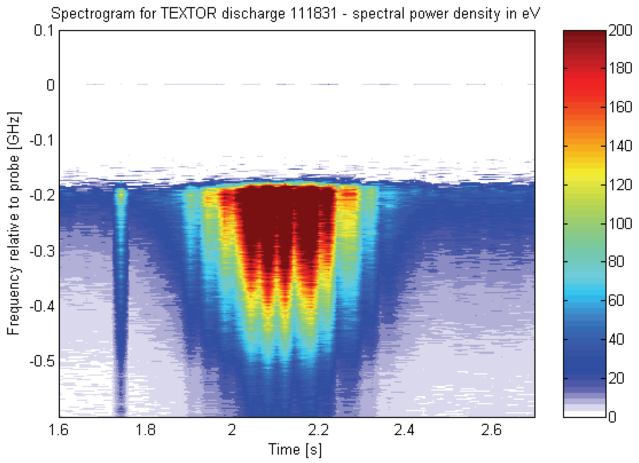

Figure 22. The spectrogram obtained from the oscilloscope in TEXTOR discharge 111831. The receiver beam was swept across the probing beam and at the time of overlap between the beams (from 1.9 to 2.3 s) the CTS signal is clearly seen – including modulations due to sawtooth activity. Note that the frequency scale is relative to the probing frequency. The range from 0 to -0.2 GHz is attenuated by two 60 dB notch filters.

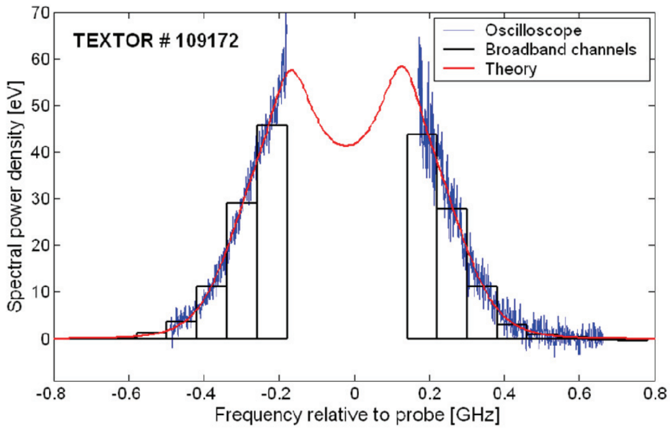

Figure 23. CTS spectra for TEXTOR discharge 109172. Blue: average spectrum measured with the oscilloscope. Black: spectrum measured with the standard low-resolution channels. The width of each bar corresponds to the channel bandwidth. Red: theoretically calculated spectrum for plasma parameters relevant to this discharge. The frequency scale is here relative to the gyrotron frequency.

It may be noted that while experiments with the oscilloscope have successfully demonstrated the diagnostic potential of CTS measurements with high frequency resolution, the bandwidth of the recorded signal and the integration times are severely restricted when using this technique. The technique is also technically cumbersome and time consuming to work with as the equipment cannot be permanently installed on the receiver. It is therefore not a viable path towards a routine diagnostic. For 2011, we have therefore proposed to purchase a fast digitizer card (model NI PXIe-5186) from National Instruments to solve these shortcomings. This card has a bandwidth of 5 GHz at sample rates up to 12.5 G samples/s, and it can be interfaced with the CTS receiver at AUG in a permanent setup. The group has already made investments towards such a system including the purchase of an NI PXI Express bus which will enable rapid transfer of the recorded data and thereby longer integration times. The remaining component is the fast digitizer card which will complete the new acquisition system and enable routine measurements with high frequency resolution. Such measurements will allow plasma composition diagnostics by CTS, and when performed in conjunction with fast ion CTS measurements they will support the data analysis and permit greater confidence in the results as more detailed information on thermal bulk ion populations can be included. Additionally, it will be possible to accurately monitor the frequency of the probing radiation, and by resolving secondary emission limited to narrow frequency ranges (e.g. due to NBI induced instabilities or due to ICRH) such effects may be removed from the spectrum and will not influence the inferred velocity distributions.

1. M. Stejner, S. K. Nielsen, S. B. Korsholm, M. Salewski, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P. K. Michelsen, D. Moseev, A. Bürger, M. Kantor, and M. de Baar, Review of Scientific Instruments **81**, 10D515 (2010).

2.3.12 Overview of the CTS at ASDEX Upgrade

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The CTS diagnostic installed on ASDEX Upgrade uses the dual frequency gyrotron as the probe. The 105 GHz frequency mode is used as the probing radiation where power up to 725 kW for 10 seconds has been attained. In 2010, due to the long shut down of ASDEX Upgrade for installation of the in-vessel B-coils for resonant magnetic perturbation, there were no CTS experiments in 2010. However progress was made in the CTS system on the hardware and analysis methodology.

A design for a major upgrade of the collective Thomson scattering (CTS) diagnostic on ASDEX Upgrade has been carried out in 2010 (see Sections 2.3.18 and 2.3.19). Presently, the CTS system is coupled to the ECRH transmission line via moveable quasi-optical mirrors located in the matching optics unit located in the gyrotron hall. The new design directly couples to the ECRH waveguides via RF switches designed by Risø DTU in collaboration with the ECRH group at IPP Greifswald and the plasma research group at the University of Stuttgart. The complete CTS hardware will be relocated to a section of the NBI control room where the waveguides are easily accessible. In addition to a more robust quasi-optic design, one of the many advantages of this upgrade is the added flexibility to easily change the receiver transmission line allowing different scattering geometries. This also enables the CTS to be independent to one particular gyrotron as its probing source. Furthermore, an additional receiver (formally located at TEXTOR) will be installed allowing two simultaneous measurements of the fast ion distribution at different locations in the plasma. The RF switches and the new quasi-optics components are scheduled to be completed in 2011.

Analysis of the data from the 2008 CTS campaign on ASDEX Upgrade concluded that the extraction of the spectra from the electron cyclotron emission (ECE) background required better temporal resolution. Typical gyrotron modulation frequency was in the range of 250 Hz where the gyrotron power was modulated between 0 and 100% of the full power (digital modulation). The strongly varying ECE background on ASDEX

Upgrade, mainly due to ELMs, required a faster gyrotron modulation. Due to the gyrotron frequency chirp, 250 Hz was the effective maximum of the digital modulation technique. However, much higher modulation frequencies up to 25 kHz can be achieved by modulating the power between 25% and 100% (analogue modulation) – a modulation technique usually used for NTM stabilization on ASDEX Upgrade. Feasibility studies of applying such a technique for CTS experiments is described in Section 2.3.13 where it was concluded that analogue modulation significantly increases the accuracy of the ECE background subtraction in H-mode plasmas. In addition, the software tools that infer the fast ion distribution were adapted to take into account the gyrotron's power and frequency difference between the two phases. Inference tests were made with fast ion synthetic fast ion data with success using this technique (Section 2.3.13).

One of the Risø DTU EFDA tasks WP-DIA-01-01 concerns comparison of confined fast ion results from the CTS and the FIDA diagnostic of the same discharges on ASDEX Upgrade. Both diagnostics are based on fundamentally different approaches hence their weighting function, which describe the relationship between the fast ion distribution function and the diagnostic measurement (CX radiation for FIDA and scattered signal for CTS) is different. Therefore, studies of the weighting function been developed for the CTS at ASDEX Upgrade. The weighting function for CTS will depend on the scattering geometry. The study optimizes the CTS scattering geometry needed in order to match FIDA's weighting function during an experiment to enable better comparison (see Section 2.3.23).

As part of the collaboration with IPP, a 140 GHz based notch filter has been designed and constructed for use on the ECE system on AUG (see Section 2.3.20). The broad band notch filter attenuates stray radiation from all 140 GHz gyrotrons while keeping a very low insertion loss over the ECE frequency coverage. The notch filter was tuned and installed in 2010 which enabled a better central coverage of the ECE during ECRH heating which resulted in significantly improving the physics exploitation during ECRH heating. In the past, the magnetic field was slightly decreased moving the resonance to the high field side to have ECE access to the central region during ECRH.

2.3.13 Development of analysis tools for CTS measurements with rapid probe power modulation

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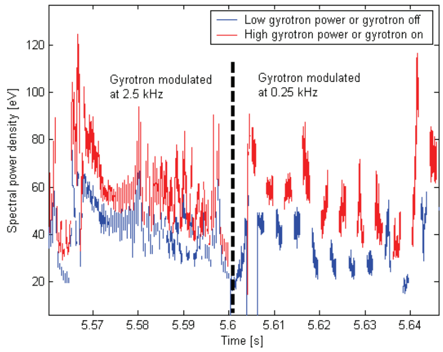
The signal measured by a CTS system operating in the microwave range of frequencies is comprised of the CTS signal itself and a background signal which mainly originates from electron cyclotron emission (ECE) near the plasma edge. At AUG the spectral power density in the background can be on the order of 50-100 eV while the spectral power density in the CTS signal is of the order of a few eV. It is therefore important to accurately distinguish between the two components, and in order to separate them the gyrotron power is modulated. In the past campaigns, the modulation pattern typically consisted of on/off periods: 3 ms periods with no gyrotron power (off periods) and 2 ms periods with full gyrotron power (on periods). The background level measured in the off periods could then be used to estimate the background level during the on periods. This background subtraction technique was developed for the CTS diagnostic at TEXTOR and has been highly successful for measurements in L-mode plasmas. However, the increased fluctuation level in the ECE background during measurements in ELMy H-mode plasmas at AUG lead to lower accuracy in the background subtraction which motivated a renewed effort to develop alternative techniques.

The most promising alternative technique depends on a significant increase in the gyrotron modulation rate. By increasing the gyrotron modulation frequency from 0.2 kHz to frequencies above 2 kHz, it becomes possible to temporally resolve fluctuations in the ECE background mainly caused by ELMs (which typically have a timescale of a few milliseconds). Thus, the increased temporal resolution in turn permits a much higher accuracy in the background subtraction. However, the increased modulation frequency also creates new challenges which necessitated adaptations in the analysis software.

This high level of gyrotron modulation frequency can only be achieved by sustaining the beam current in the gyrotron tube and modulating the power levels (the lower levels are typically 25% of the higher output power). Further, there is a small difference in the gyrotron frequency between the two settings (the gyrotron frequency is 105 GHz and changes by roughly 10-15 MHz). To address these issues, new software tools have been developed for background subtraction which can take advantage of the higher modulation frequency while accounting for the new high/low power modulation pattern. In addition, the theoretical CTS model [1] used to infer fast ion distributions from the measured CTS spectra was adapted to include the effects of variations in the probe frequency.

Prior to experimental tests, numerical tests were carried out to access the accuracy of the background subtraction and the ability to infer fast ion velocity distributions from CTS spectra with varying probe frequency. The tests demonstrated that the accuracy of the background subtraction is significantly improved (the rms error in the result can be decreased a factor of 5), and that the variations in probe frequency do not impair the ability to analyze the data. Recently, the first experimental tests of the new operating regime were conducted in early 2011 during H-mode plasmas at AUG. At the time of writing, initial analysis indicates that the tests were fully successful, and that the analysis tools perform as expected. It is therefore expected that the techniques developed for CTS measurements with rapid probe power modulation will be used extensively at AUG during 2011, and it is possible that it will become the standard operating scenario for the CTS diagnostic at AUG. Figure 24 shows an example of data taken with high and low gyrotron modulation frequencies. Figure 25 shows an example of results from the numerical tests of the ability to infer fast ion velocity distributions from CTS spectra with different probe frequency in the two power levels.



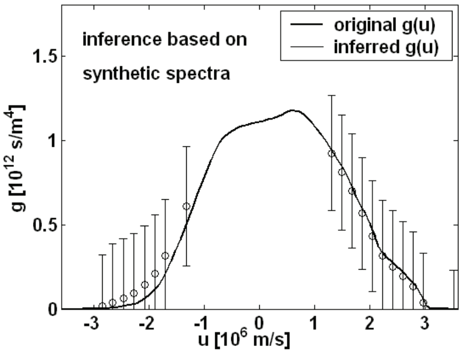


Figure 24 An example of data taken with different gyrotron modulation rates in AUG discharge 26404. To the left of the thick dashed line the gyrotron is modulated between high and low output power at 2.5 kHz. To the right, it is modulated with the on/off power levels at 0.25 kHz. The CTS signal is the difference between the blue and the red lines. With the high modulation rate fluctuations in the background due to ELM activity can be temporally resolved and do not degrade the accuracy of the background subtraction.

Figure 25 An example of numerical test results for inference of fast ion velocity distributions based on CTS spectra with varying probe frequency. A synthetic spectrum including the effects of varying probe frequency was fitted assuming realistic uncertainty levels for all input parameters. The figure shows the original and the fitted/inferred 1-D projection of the fast ion velocity distribution, g(u). The two are consistent within the error bars of the fit showing that the original distribution was correctly recovered.

1. H. Bindslev, J. Atmos. Terr. Phys. 58, (1996)

2.3.14 Preparation for experiments HCD-01: NBI off-axis current drive efficiency

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The aim of the task is to directly compare confined fast ions between the on-axis and off-axis NBI beams on ASDEX Upgrade in order to shed light on the lack of current drive efficiency for off-axis NBI reported in various references. Due to the long shut down of AUG in 2010, the task was extended 6 months into 2011. However, past experiments have revealed technical anomalies where the modulating gyrotron interfere with the NBI box with the off-axis beams which causes the source to trip. Both systems share the same high voltage power supply. Coordination of both the ECRH and NBI groups prompted technical tests to solve the interruption. TRANSP/NUBEAM simulations have been carried out by IPP for sensitivity studies of fast ion distribution with different plasma parameters. In late 2010, the Risø DTU group was granted access by the Princeton Plasma Physics Laboratory to run the TRANSP code as part of the collaboration with IPP.

2.3.15 Overview of task coordination DIA-01-01: Measurement of confined alpha particles

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The goal of the EFDA task WP-DIA-01-01 is to compare fast ion results between all fast ion diagnostic for the same discharges on ASDEX Upgrade. These include, the CTS, the FIDA, neutral particle analyzer, gamma ray spectroscopy (ENEA - CNR Association), and the fast ion loss detector. Due to the long shut down of ASDEX Upgrade for installation of the in-vessel B-coils for resonant magnetic perturbation, there were minor experimental tests performed in late 2010, hence the task has been extended for six months. This task requires coordination between multiple associations to optimize the operating scenarios, the diagnostic set-ups, and simulation tools. As mentioned in Section 2.3.12, an additional CTS receiver is planned to be installed as part of the major upgrade of the CTS. The additional receiver (formally at TEXTOR) has been tested and modified for AUG. This will enable two simultaneous measurements of the confined fast ion distribution function. The CTS and FIDA diagnostic both measure local confined fast ions. Hence, CTS weighting function studies have optimized the scattering geometry to facilitate the comparison between the two diagnostics. Gamma ray spectroscopy relies on the nuclear reactions between fast deuterium ions and nitrogen ions. ICRH scenario development has been carried out in order to couple sufficient power to the plasma which is a challenge in a machine with tungsten as the first wall material. Use of theoretical tools is of course a large part of this task. The simulation tools TRANSP/NUBEAM (IPP) and ASCOT (TEKES) are used for interpretation. In addition, synergy effects between ICRH and different NBI sources at AUG has started by IPP's theoretical group in order to investigate the best NBI source improve the power coupling of ICRH for fast ion generation.

2.3.16 NTM detection using the CTS receiver

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In order to verify the feasibility of the NTM detection and control unit using two different launching mirrors the following assumptions and calculations were made.

During a shot, only the elevation angle (machine angle) can be varied. The rotation angle (machine angle) has to be set beforehand. This study is preliminary.

Refer to Figure 26. The blue cylinder depicts the radius corresponding to the ECRH deposition radius in the tokamak and the red section of a torus depicts a magnetic flux surface where we expect to have NTM. The radius of 1.3 meters has been chosen as an example. Launching energy to this magnetic flux surface can only be achieved by launching microwave radiation along the intersection of the magnetic flux surface with the resonance surface (yellow lines in Figure 26)

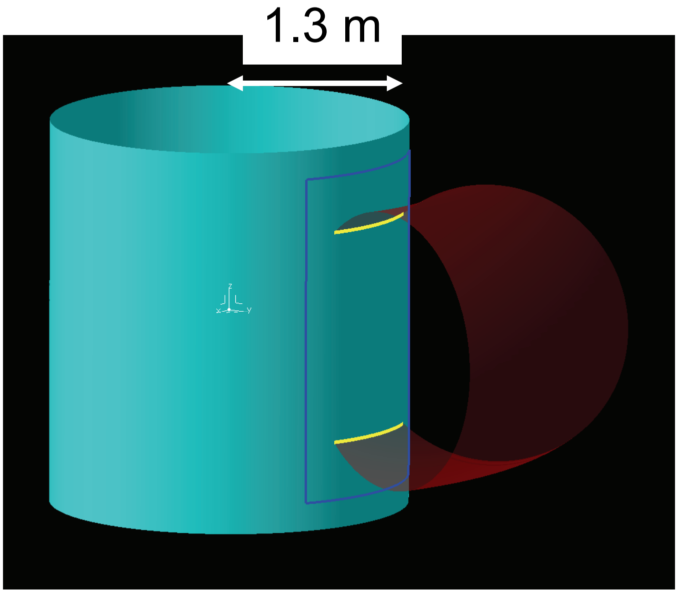

Figure 26: ECRH deposition surface (blue) and magnetic flux surface (red) where an NTM is expected.

For this calculation refraction of the beam in the plasma is neglected. Both mirrors (#1 and #2 of the antenna unit) are steered to the same angle of rotation and elevation angles (machine angles). Both beams intersect the resonance surface at different positions. The vertical difference for both beams at the intersection point is shown in Figure 27. For extreme rotation angles (+/- 30°) the two beams intersect the resonance surface with a vertical offset of up to 50 mm and for radial beam geometry, the vertical offset is 0. If an extreme rotational angle is required for the NTM stabilization, the beams should point in the equatorial plane to keep the vertical offset small. The vertical offset is a guideline. If an NTM is detected at a certain location (along the yellow lines in Figure 26) then the vertical offset will indicate how far off the launching beam would be in the vertical direction.

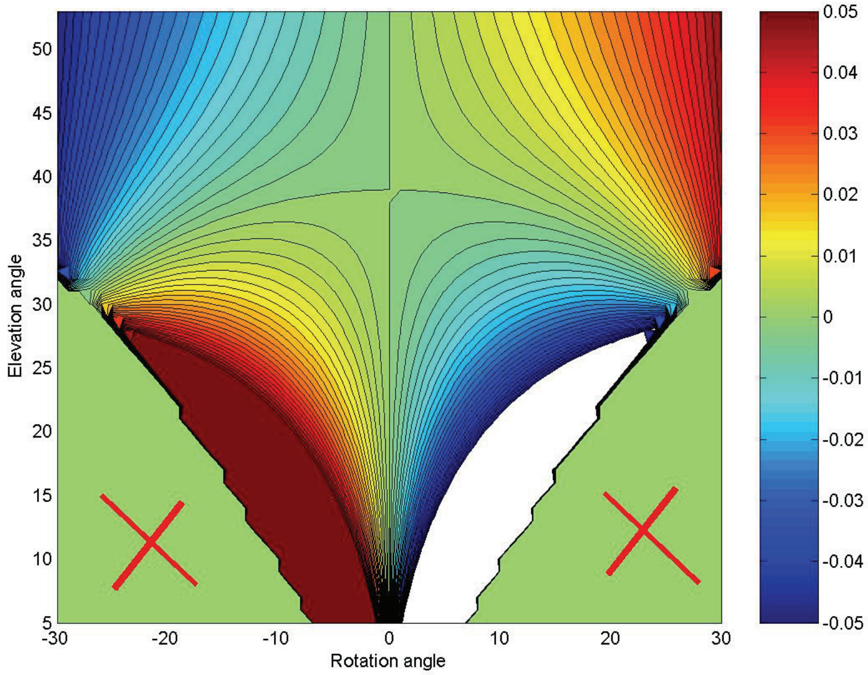

Figure 27. See text. The red Xs indicate areas where the beams do not intersect the resonance surface. The unit of the color bar is [m].

2.3.17 Modification of an existing CTS receiver to be implemented at ASDEX Upgrade

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The CTS receiver which was previously installed at TEXTOR has been modified to be applicable to ASDEX-Upgrade. The optical transmission line from the horn antenna to Polarizer 2 was left unchanged (see Figure 29). Mirror 2 was designed in a way that it converts the radiation coming from the waveguide to be accepted by the remaining transmission line. Figure 28 shows the Gaussian beam dimension for 110 GHz (as it was originally designed for at TEXTOR) and for 105 GHz, which will be the case at ASDEX.

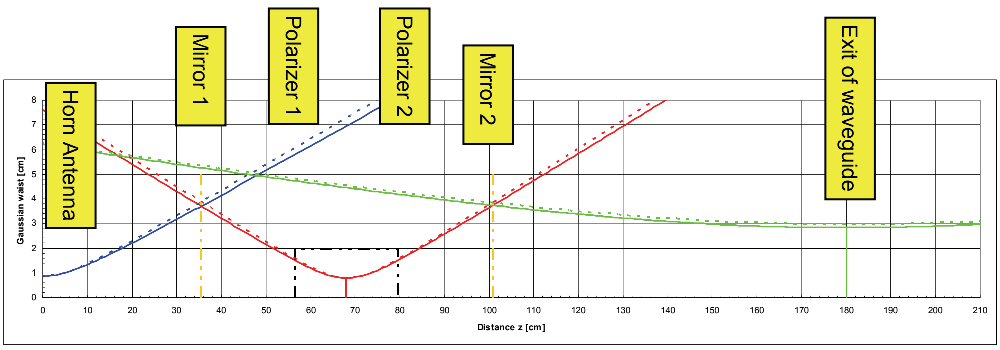

Figure 28. Gaussian beam dimension for 110 GHz (solid lines) and for 105 GHz (dashed lines).

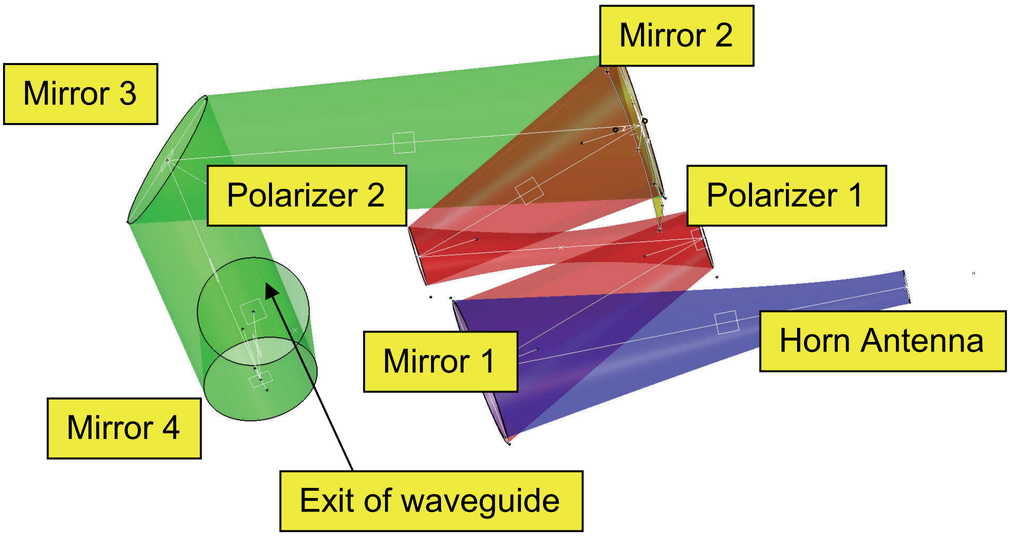

Figure 29. CATIA drawing of the quasi optic transmission line.

In order to characterize the transmission line with the newly designed and built Mirror 2, a microwave source was attached to the horn antenna and the beam intensity distribution was measured at the location of the waveguide exit. Figure 30 shows a contour plot and the profile of the beam. The measured beam dimension is in good agreement with the calculation. Characterization of the polarizers for the new frequency is in progress.

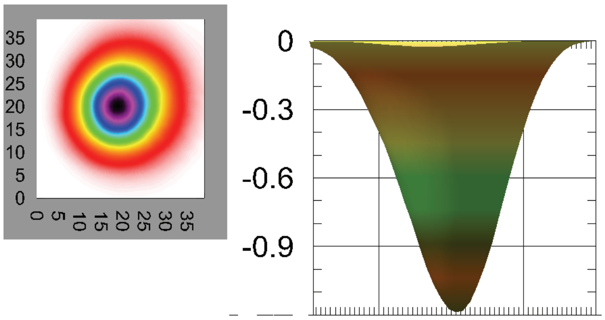

Figure 30. Beam pattern of the Gaussian beam at the location of the waveguide. The dimensions of the contour plot are cm and the intensity profile is in arbitrary units.

2.3.18 Final design and manufacture of the RF switch in the new optical transmission line for the CTS receiver on ASDEX Upgrade

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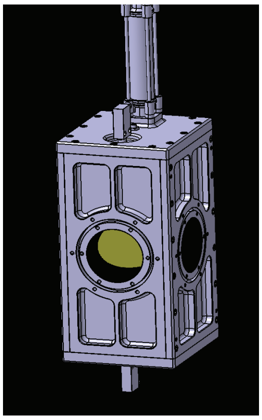
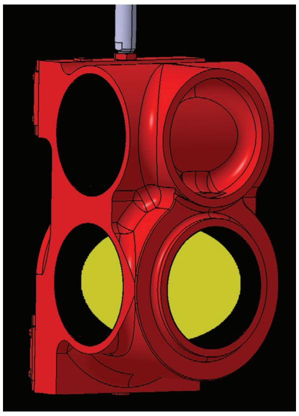
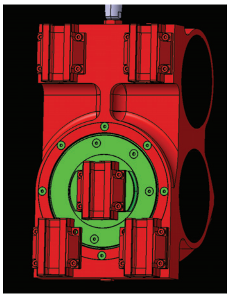
For the new location of the CTS receiver at ASDEX Upgrade, the gyrotron transmission line then has to be intercepted by means of an RF switch. In the ECRH mode the switch will transmit the gyrotron radiation to the tokamak via an inserted mitre bend. In CTS mode, the CTS receiver can see through the gyrotron waveguide into the tokamak. Originally, two designs were made for the RF switch: One with a round piston which is easier to built and less complex but has the disadvantage of cutting the corrugations under an angle. The other solution has a rectangular piston, were the cuts are perpendicular to the corrugations of the waveguide, but it is a more complex design. The switch shall have three positions: (1) gyrotron power can launched through the RF switch and along the waveguide, (2) the CTS receiver can see inside the tokamak for CTS measurements, and (3) the receiver can see towards the gyrotron for stray radiation measurements. We decided to go for the solution with the rectangular piston. The design drawings of the switch are shown in Figure 31, while many of the manufactured parts are shown in Figure 32. The design, manufacture and assembly are performed at Risø DTU.



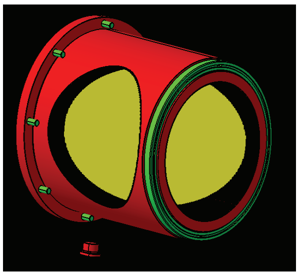
a) Housing of the switch with a rectangular piston. The mirror of the mitre bend can be seen (yellow)



b) Rectangular piston. The lower level contains the mitre bend mirror inlet (yellow). The upper level is just a hole through.



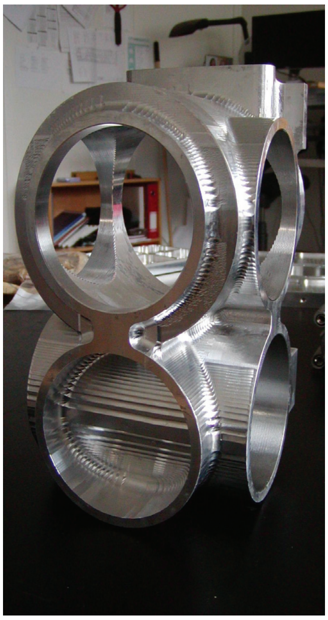
c) Rectangular piston seen from behind. The green part is a rotating inlet containing the mitre bend mirror to allow a switching between tokamak and gyrotron box



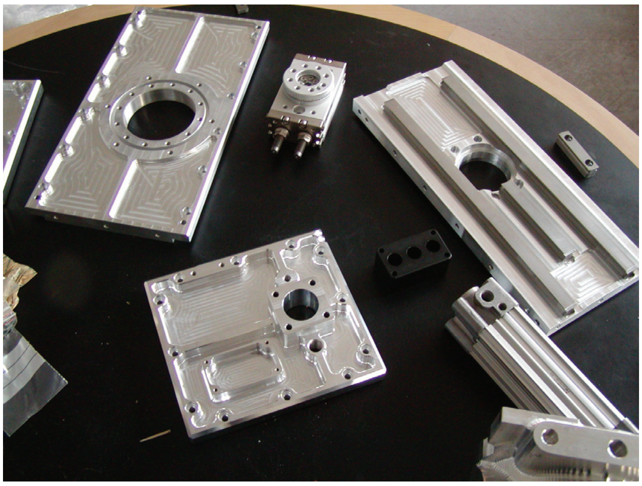
d) Rotating inlet (red) with mitre bend mirror (yellow)

Figure 31.a-d. Design drawings of the RF switch with rectangular piston.

a) Rotating inlet with mitre bend mirror



b) Rectangular piston. The upper level carries the rotatable mitre bend mirror inlet. The lower level is just a hole through.



c) Parts of the switch

Figure 32. a-c. The manufactured parts of the RF switch. All parts have been machined at Risø DTU.

2.3.19 Design of the new mirror optics unit for the CTS receiver on ASDEX Upgrade

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The radiation coming from the tokamak is transmitted from the corrugated transmission line to the optical transmission line via the RF switch described in Section 2.3.18. It is assumed that the beam is Gaussian with the waist at the exit port and a waist radius of 28.31 mm. Figure 33 shows the schematic of the quasi-optics and the numbers in the cyan boxes denote the position. The exit port of the waveguide is at position 1. The red beam shown in the CATIA drawing in Figure 33 corresponds to the 105 GHz beam where the border is 1.6 times the Gaussian width of the beam. This size of the mirrors ensures that 99.4% of the radiation is captured. The 140 GHz beam lies inside the 105 GHz beam and is not depicted here. The horn antennas for 105 GHz have been designed manufactured (see Figure 34) at Risø DTU.

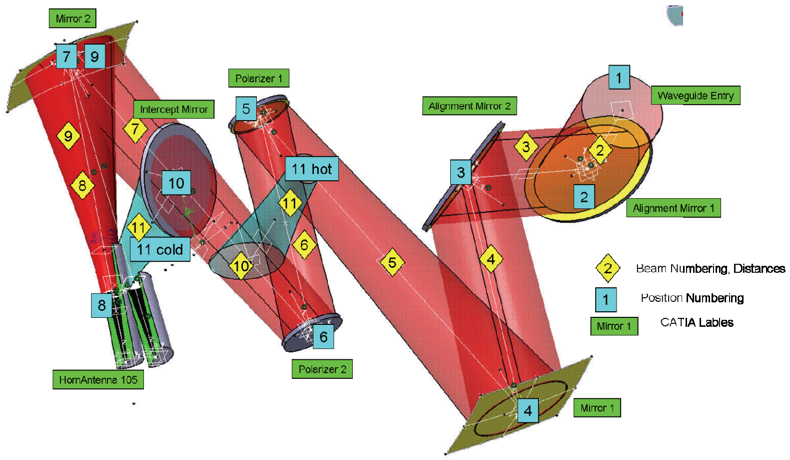

Figure 33. Transmission line. The beam is shown in red and represents 1.6 times the Gaussian width. The blue labels number the optical components and the yellow labels number the beam legs.

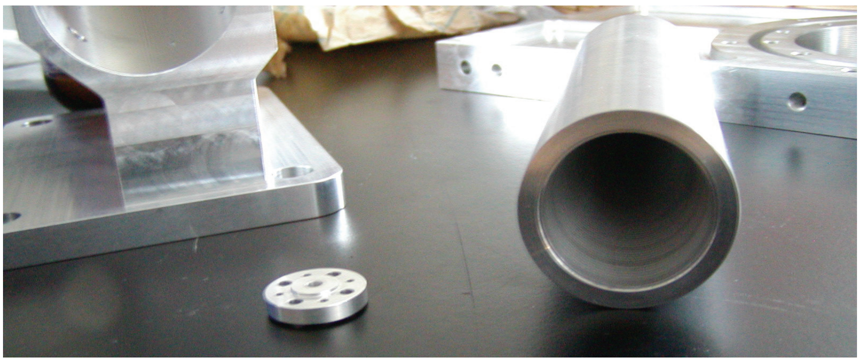

Figure 34. Horn antenna and adapter disk (to convert to existing waveguide components)

2.3.20 140 GHz Broadband notch filter design for millimeter wave diagnostics

*V. Furtula, P.K. Michelsen, F. Leipold, S.B. Korsholm, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, T. Johansen**
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Notch filters are required in mm-wave plasma diagnostic systems to protect the receivers from intensive stray radiation from gyrotrons. Here we present a design of a notch filter with a center frequency of 140 GHz, a rejection bandwidth of approximately 900 MHz, and a typical insertion loss below 2 dB in the passband of ±9 GHz. The design is based on a fundamental rectangular waveguide with 8 cylindrical cavities coupled by T-junction apertures formed as thin slits. Parameters that affect the electrical performance of the filter such as physical lengths and conductor materials are discussed. The excited resonance mode in the cylindrical cavities is the fundamental TE11. The performance of the constructed filter is measured using a vector network analyzer (VNA) monitoring a total bandwidth of 30 GHz. The notch filter is simulated using a 3-D electromagnetic simulator in CST.

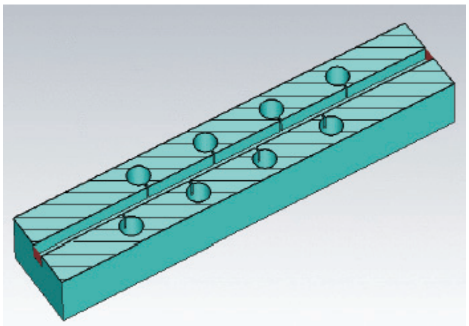

Figure 35. Simulated notch filter from CST Microwave Studio.

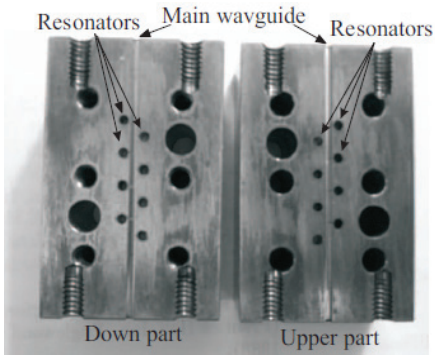

Figure 36. The realized notch filter from the Risø DTU machine shop.

Simulations show that narrower rejection bandwidths are achievable by increasing the slit depth. The key design parameters such as center frequency f0, 3-dB rejection bandwidth BW3dB, and selectivity steepness around 3-dB points are estimated by tuning the geometry of the coupling slit and the cavity lengths. The simulation data shows that relatively small geometrical changes have considerable impact on filter parameters such as center frequency f0, 3-dB bandwidth BW3dB, and selectivity steepness. This notch filter has been integrated in the ASDEX Upgrade ECE diagnostic which enabled the possibility of resolving electron temperature through to the plasma center where in the past ECE temperature measurements on ASDEX Upgrade were only possible to a rho = 0.15 with 140 GHz gyrotron.

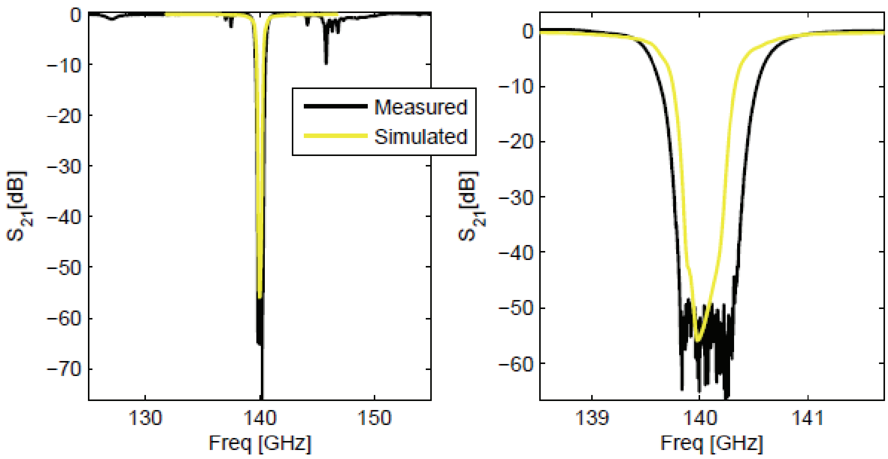

Figure 37. Simulated and measured notch filter S-parameters. The graph to the right is a zoom-in around the notch frequency of 140 GHz.

2.3.21 105 GHz notch filter design for Collective Thomson scattering

*V. Furtula, P.K. Michelsen, F. Leipold, S.B. Korsholm, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, T. Johansen**
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Millimetre wave CTS receivers for detection of energetic particles require rejection bandwidth around 200 MHz and passband coverage of minimum ±5 GHz. A mm-wave notch filter with 105 GHz center frequency, more than 20 GHz passband coverage, and 1 GHz rejection bandwidth has been constructed. The design is based on a fundamental rectangular waveguide with cylindrical cavities operating in fundamental TE11 mode coupled by narrow iris gaps, i.e. small elongated holes of negligible thickness. We use electromagnetic simulator CST Microwave Studio to study the sensitivity of the notch filter performance to changes in geometry and in material conductivity within a bandwidth of ±10 GHz. The constructed filter is tested successfully using a vector network analyzer (VNA) monitoring a total bandwidth of 20 GHz. The typical insertion loss in the passband is below 1.5 dB, and the attenuation in the stopband is approximately 40 dB.

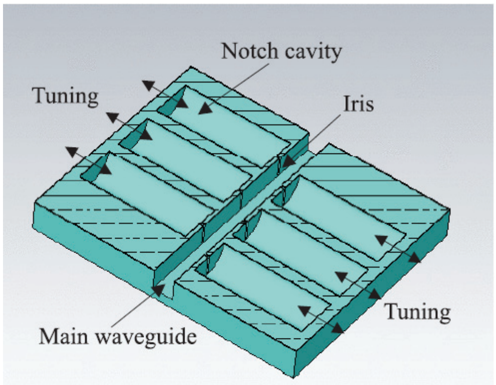

Figure 38. Simulated 105 GHz notch filter from CST Microwave Studio.

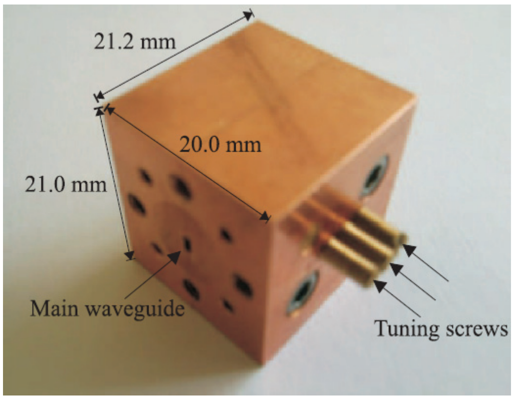

Figure 39. The realized notch filter.

The key filter parameters such as center frequency f0, 3-dB rejection bandwidth BW3dB, and shape factor were investigated by adjusting the filter geometry slightly and simulating it using CST. The center frequency of the filter is found to be sensitive to the cavity length, which is beneficial for the dynamic notch shifting across the spectrum.

In the future we should consider designing a notch filter using the third-order mode TE01, since then we achieve much higher Q factor for a cylindrical cavity, compared to TE11 mode. TE01 mode will give us very narrow and deep notch. The disadvantage with TE01 mode is that we get narrower pass band coverage.

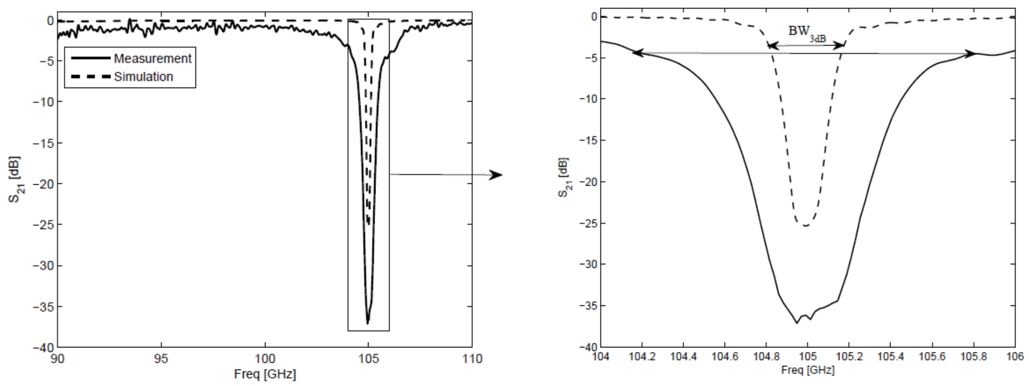

Figure 40. Simulated and measured notch filter S-parameters. The graph to the right is a zoom-in around the notch frequency at 105 GHz.

2.3.22 140 GHz MMIC for fusion diagnostics

*V. Furtula, P.K. Michelsen, F. Leipold, S.B. Korsholm, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, T. Johansen**
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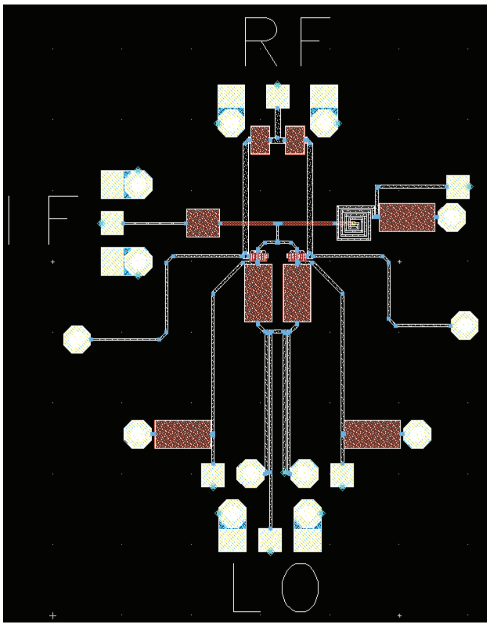
In the CTS receiver RF line we have substantial losses due to several waveguide components and due to large conversion losses coming from the mixer. Losses in the RF line have large impact on the system noise figure (NF) so therefore losses close to the signal source must be minimized. A subharmonic mixer (SHM) with low conversion loss is about to be designed using D007IH (InP MHEMT with gate length 0.07 µm) OMMIC foundry service. The RF input frequency is in range from 135 to 145 GHz. The output IF frequency is in the range from 5 to 15 GHz. The local oscillator (LO) frequency is hereby 65 GHz, which is half of what is usually required for direct conversion mixers. The mixer topology has form as balanced differential pair where RF input signal is applied to the source, 2 LO signals with modulation 180° out of phase are applied to the gate, and the IF output signal is taken out at drain.



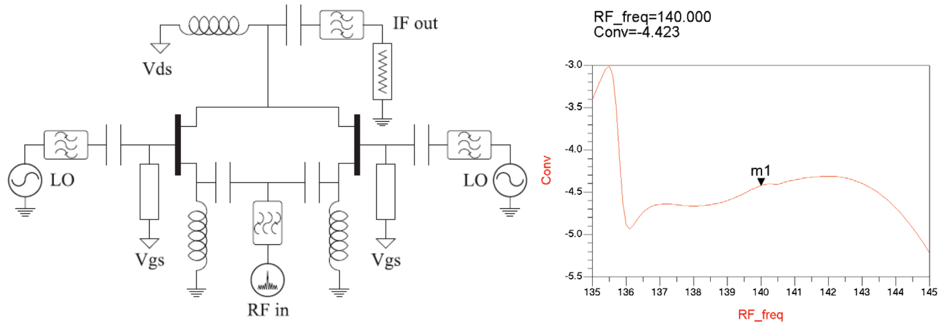


Figure 41. 140 GHz sub harmonic mixer using half-LO frequency to drive the mixing process; (Upper) ADS simulation layout; (Lower-left) Circuit topology of the mixer; (Lower-right) Conversion simulation.

The first simulations of the mixer shown in the upper figure are indicating that we have a good chance of achieving conversion better than -5 dB, which is much better than what we achieve using direct conversion mixers (~ -10 dB).

2.3.23 Velocity space interrogation regions of fast ion collective Thomson scattering at ITER

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The proposed ITER CTS system is designed to measure time-resolved fast ion velocity distributions in several measurement volumes simultaneously, satisfying the ITER measurement requirements for fusion alpha diagnostic. The time resolution is 40 ms. The spatial resolution is 1/10th of the minor radius for 7 − 10 different locations [1]. The proposed ITER CTS system contains two subsystems, a forward scattering system with a receiver on the high magnetic field side of the tokamak vessel and a backscattering system with a receiver on the low magnetic field side [2]. While the backscattering system is part of the diagnostic system of ITER, the forward scattering system is currently not included. Using the recent concept of weight functions and using numerical simulations it is possible to find the interrogation regions in (energy, pitch)-space of each CTS system. Backscattered radiation received with an antenna on the low field side reveals fast ions with pitch up to |p|=0.5-0.8, depending on the frequency shift of the scattered radiation. An example weight function is plotted in Figure 42 for the backscattering system. The grey lines show an example alpha distribution. The coloured region shows the interrogation region of a particular resolved velocity, u=10^7 m/s. Only ions in the coloured regions can elicit a response in the CTS receiver for the backscattering system at the particular resolved velocity. This example shows by no means the entire interrogation region of a CTS measurement. For other resolved velocities, which are simultaneously available in a CTS measurement, the interrogation region will have its minimum resolved energy at a different place while its shape will be similar. Forward scattered radiation received with an antenna on the high field side reveals passing ions with pitch larger than |p|=0.6-0.8, also depending on the frequency shift. The seemingly different shape of the interrogation region is shown in Figure 43. An extra benefit of having both systems is that it is also possible to measure a 2D velocity distribution, if simultaneous measurements along two resolved directions are available, and anisotropy can be studied.

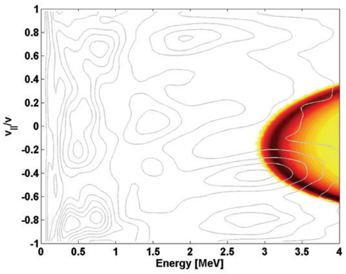

Figure 42. Interrogation region of the backscattering system for a particular resolved velocity channel u=10^7 m/s.

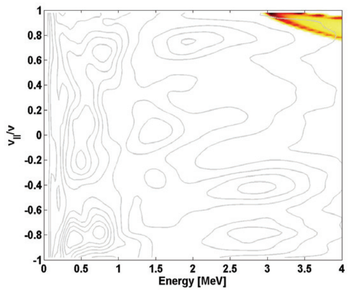

Figure 43. Interrogation region of the forward scattering system for a particular resolved velocity channel u=10^7 m/s.

1. Bindslev et al (2004) Rev. Sci. Inst. 75(10) 3598
2. Meo et al (2004) Rev. Sci. Inst. 75(10) 3585

2.3.24 Feasibility of plasma rotation measurements by CTS

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The velocity distribution of thermal ions can influence collective Thomson scattering (CTS) measurements at low frequency shifts. The measured spectrum will be Doppler shifted due to plasma rotation and the velocity of the thermal bulk ions can be inferred from the resulting asymmetry of the CTS spectrum around the probing frequency. To assess the feasibility of plasma rotation measurements by CTS we conducted a sensitivity study modeling the theoretically expected accuracy of such measurements. The thermal bulk ions are represented by drifting Maxwellian velocity distributions with the drift velocity, V_i, in the direction of the magnetic field. We calculate the expected uncertainty with which V_i could be inferred within the framework of the Bayesian method of inference frequently used to interpret CTS measurements [1]. The Bayesian approach allows inclusion of prior knowledge from other diagnostics about all model parameters, and the resulting posterior uncertainty includes the effects of uncertainties in the prior information. We assume that no prior information exists about Vi to ensure that the posterior uncertainty for the drift velocity includes only the information contained in the CTS spectrum. For all other parameters we assume conditions relevant to an NBI heated H-mode plasma at ASDEX Upgrade (AUG) - specifically we use the parameters and prior uncertainties reported for discharge 24089 analyzed in [2]. We further assume that the CTS receiver incorporates a fast acquisition system capable of recording the spectrum with a frequency resolution of 2 MHZ in a 1 GHz wide frequency range centered on the probe frequency. Such high resolution measurements were recently performed at TEXTOR using a fast oscilloscope to digitize the CTS signal [3].

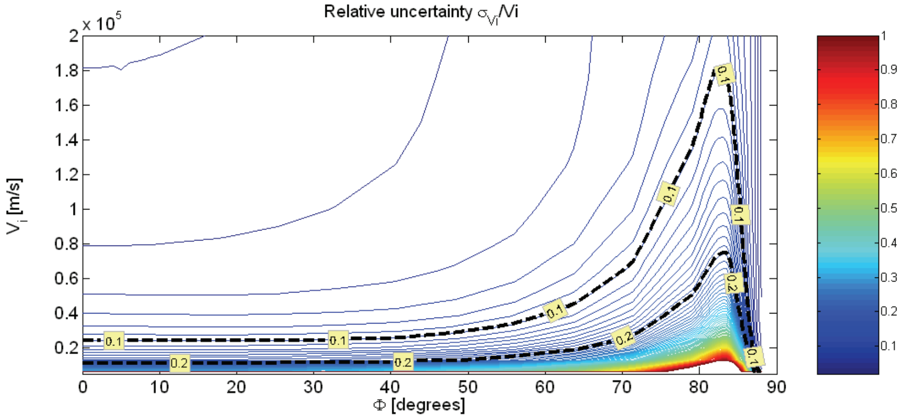

Figure 44. Relative uncertainty in V_i as a function of V_i and $\Phi=\angle(k^\delta, B)$. The figure shows 100 linearly spaced contours in the interval $\sigma_{Vi}/V_i = 0$ to 1 (i.e. no contours are shown in the lower left where, $\sigma_{Vi}/V_i > 1$). The thick dashed lines marks the contours for $\sigma_{Vi}/V_i = 0.05, 0.1, 0.2$ and 0.3.

Results of the sensitivity analysis are illustrated in Figure 44 which shows the theoretically expected relative uncertainty (one standard deviation) in the drift velocity, σ_{Vi}/V_i, as a function of V_i and the angle $\Phi=\angle(k^\delta, B)$. Here k^δ is the wave vector of the plasma fluctuations resolved by the CTS measurement and B is the magnetic field in the scattering volume. The CTS spectrum is sensitive to the projection of the ion velocity distribution along k^δ. The direction of k^δ, which is determined by the orientation of the probe and receiver beam antennas, is therefore among the most important parameters influencing σ_{Vi}. The results indicate that rotation measurements with relative accuracy better than 20% should be feasible for velocities above 10 km/s and $\phi < 60°$. Low uncertainties are also found at values of ϕ close to 90° . For such scattering geometries the CTS spectrum contains highly detailed structures originating from the combined effects of ion cyclotron motion and weakly damped ion Bernstein waves on the spectrum. These structures significantly increase the information content in the spectrum thus increasing the accuracy, but they can only be resolved with the high frequency resolution assumed in these calculations. The high frequency resolution further strongly decreases any uncertainty concerning the frequency of the probing radiation (since it can be directly monitored). Without the ability for measurements with high frequency resolution the drift velocity could still be inferred in scattering geometries with k^δ nearly parallel to the magnetic field, but uncertainties would be higher since the spectrum would contain less information, and any drift in the probing frequency would add systematic uncertainties to the measurements which could be difficult to quantify.

In summary, results from the sensitivity study indicate that rotation measurements by CTS with relative accuracies better than 20% should be possible at AUG. Measurements with high frequency resolution by means of a setup similar to that used at TEXTOR [3] offer the highest accuracies and the greatest experimental flexibility. These results were illustrated for a particular plasma scenario relevant to an NBI heated H-mode plasma at AUG. Broader parameter scans indicate that the conclusions are robust to changes in plasma conditions and that similar accuracies could be achieved under conditions relevant to ITER. Proof-of-principle experiments could be conducted with existing hardware by connecting the CTS receiver at AUG to the fast oscilloscope previously used for a similar purpose at TEXTOR. For routine measurements a permanent acquisition system for measurements with high frequency resolution would be preferable. Such a system could be based on fast ADC cards currently available from commercial suppliers, and it would further enable measurements of plasma composition using the methods developed under WP10 DIA-01-03. Interpretation of measured data should be feasible with existing software also developed in part under WP10 DIA-01-03, but for routine measurements some adaption of the software would be required.

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2. M. Salewski, F. Meo, M. Stejner, et al, Nuclear Fusion **50**, 035012 (2010).
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2.3.25 Collaboration with the CTS team at the Large Helical Device

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The collaboration between the CTS groups at Risø DTU and at the National Institute for Fusion Science (NIFS) in Japan was continued in 2010. In early 2010 Dr. Nishiura visited Risø DTU and participated in CTS experiments at TEXTOR.

During the fall of 2010 the CTS group at NIFS invited M. Stejner from the Risø DTU CTS group to participate in CTS experiments at the Large Helical Device (LHD). The CTS diagnostic at LHD uses 77 GHz microwave probe radiation and a heterodyne receiver system similar in principle to those of the CTS systems at AUG and TEXTOR. The main aims of the LHD CTS system are to conduct ion temperature measurements and measurements of fast ion velocity distributions in the core of LHD plasmas. For this purpose the acquisition technique for measurements with high frequency resolution developed at TEXTOR and published in reference [1] could be highly useful. During the visit, a receiver setup similar to that used at TEXTOR for high resolution measurements was tested at LHD. The tests demonstrated the ability to measure spectra with high frequency resolution and further demonstrated consistency between the spectra measured with this technique and with the standard acquisition technique. Additionally, the tests permitted characterization of the effects of interference between different gyrotrons operating simultaneously in the same frequency range.

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3 Fusion Technology

3.1 High temperature superconductor coated conductor characterization and modelling

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Summary: Two different state-of-the-art high temperature superconducting coated conductor tapes based on $REBa_2Cu_3O_{6+x}$ (RE = Rare Earth and Y) have been characterized by magnetization measurements in applied fields up to B = 16 Tesla. The temperature and field scaling of the critical current compared to T = 77 K and zero applied magnetic field have been determined. The scaling has been used to extrapolate the engineering critical current density of a 24 cm x 14 cm x 0.5 cm Race Track coil. A similar scaling can be used to determine the expected engineering current density in future coils for DEMO.

Coated conductors consist of a metal substrate with several ceramic buffer layers deposited on the smooth surface. A bi-axial texture of the buffer layer is obtained either by heavily deforming a substrate made of Ni - 5 % W, whereby the metallic grains will be aligned, or by depositing MgO on the surface of a polycrystalline substrate using Ion Beam Assisted Deposition (IBAD) at an inclined angle. A final layer of the $REBa_2Cu_3O_{6+x}$ (RE = Rare Earth and Y) high temperature superconductor is then deposited and the resulting layer is also bi-axially textured allowing a super current to pass across the grain boundaries along the superconducting tape illustrated in Figure 45.

Table 1 is showing typical cross section areas of two types of coated conductors including the insulation thickness obtained in a number of Race Track coils produced at Risø DTU (Figure 46) [1]. The critical current of the coil based on the Ni-W tape (Figure 46) was found to be $I_C = 69\ A$ and is in good agreement with the expected decreased due to the magnetic field produced at $T = 77\ K$. Measurements of the quench behaviour and the AC losses of the coil are ongoing, and will be compared to coated conductor resolved finite element modelling [2].

The engineering critical current density J_e is defined as the ratio between the critical current I_C and the cross section area of the tape A_{tape} and any insulation or soldering alloy A_{spacer} in case of a coil winding or stacked conductor respectively.

$$J_e = \frac{I_C}{A_{Tape} + A_{spacer}} \qquad (1)$$

It is the engineering critical current density of a superconducting coil winding, which is one of the key parameter needed in the design of high field magnets. However the information provided from the manufactures of coated conductors is often only the critical current I_C measured in liquid nitrogen at $T = 77\ K$. One can also request a general scaling of $I_C(B,T)$ as function of applied magnetic field and temperature, but the rather fast improvement of the properties of the tapes will make it likely not to be representative for the tape used for a specific coil. Thus we have measured the hysteresis of the magnetization of the two coated conductors using a Cryogen Free Measuring System (CFMS) at Risø DTU and figure 3 and 4 is showing how the hysteresis is scaling compared to the value at $T = 77\ K$ and zero field.

The simple Bean model states that the hysteretic opening ΔM of a magnetization curve is proportional to the critical current density J_C, whereby the critical current $I_C(T = 77\ K)$ provided by the manufacture of the tape is expected to scale with the temperature and field scaling of ΔM as shown in Figure 47 and Figure 48. The obtained measurements have been used to extrapolate the current density of rotor coils for a 5 MW direct drive superconducting generator for a wind turbine and it was found that a $J_e = 70\ A/mm^2$ and $J_e = 300\ A/mm^2$ is possible in an applied field of $B = 4\ T$ and $T = 30\text{-}40\ K$ for the Ni-W and Hastelloy substrate based coated conductors respectively [1].

From a fusion point of view it is interesting to examine the scaling of J_e of the coated conductors and compare this with the target current densities of the Nb_3Sn superconducting magnets in of the ITER reactor. The cross sectional area of the Nb_3Sn strands of the CS and TF coils of ITER are $A_{CS} = 0.52\ mm^2$ and $A_{TF} = 0.53\ mm^2$ with critical currents of the order $I_{C,CS} = 150$ A and $I_{C,TF} = 250$ A at T = 4.2 K and in B = 12 Tesla. This result in $J_{e,CS} = 291$ and $J_{e,TF} = 472\ A/mm^2$ respectively [4].

The upper limit of the engineering critical current density of the coated conductors is obtained by including only the cross section area of the tape denoted $J_{e,tape}$ in table 1. The scaling factor needed to obtain the current densities of Nb_3Sn is then

$$f = \frac{J_{e,Nb_3Sn}}{J_{e,CC}} \qquad (2)$$

This gives 3.2 and 5.3 for the Ni-W tape compared and 1.0 and 1.6 when compared to the CS and TF coil respectively. Thus by looking at figure 3 and 4 it is concluded that the Ni-W tape will not provide that high a engineering current density even at T = 4.2 K. However the Hastelloy tape will at T ~ 20 K and T ~ 5 K respectively.

It should be said that the Ni-W tape is much thicker than the Hastelloy tape, because it is laminated with a thicker layer of steel compared to the thin layer of Cu on the Hastelloy tape. This illustrates very clearly that the discussion of the optimal substrate layer and final lamination of a coated conductor targeted for fusion magnets is most relevant. The above evaluation is also showing that coated conductors are expected to compete with Nb_3Sn at T = 20 K, but that operation at liquid nitrogen temperature will need considerable improvement of the current coated conductors.

Conclusion: The magnetic field and temperature scaling of two state-of-the-art coated conductors have been investigated using magnetization measurement. A race track coil holding 32 meters of the Ni-W based tape have been obtained and studies of losses and quench behaviour is ongoing. Finally the field and temperature scaling of the engineering current density J_e indicates that the current coated conductors can compete with Nb_3Sn in B = 12 Tesla at temperature around T = 20 K for the CS coil, but operation at liquid nitrogen temperature will need considerable improvements of the coated conductors.

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4. N. Koizumi, H. Murakami, T. Hemmi and H. Nakajima, *Analytical model of the critical current of a bent Nb_3Sn strand*, Supercond. Sci. Technol. **24** (2011) 055009.

Table 1. Properties of state-of-the-art coated conductors given by critical current I_C at T = 77 K, the tape width, the tape thickness, the thickness of the coil insulation obtained in [1], the resulting engineering current density of the tape and the coil winding in Figure 46.*Coil holding CC-Hastelloy is currently being wound and the number is the expected value based on the thin epoxy insulation applied to the tape.

Type	I_C (77 K) [A]	w_{tape} [mm]	t_{tape} [mm]	$t_{insulation}$ [mm]	$J_{e,tape}$ [A/mm^2]	$J_{e,coil}$ [A/mm^2]
CC- NiW	95	4.8	0.22	0.1	90.0	61.8
CC- Hastelloy	125	4.2	0.1	0.06	297.6	186*

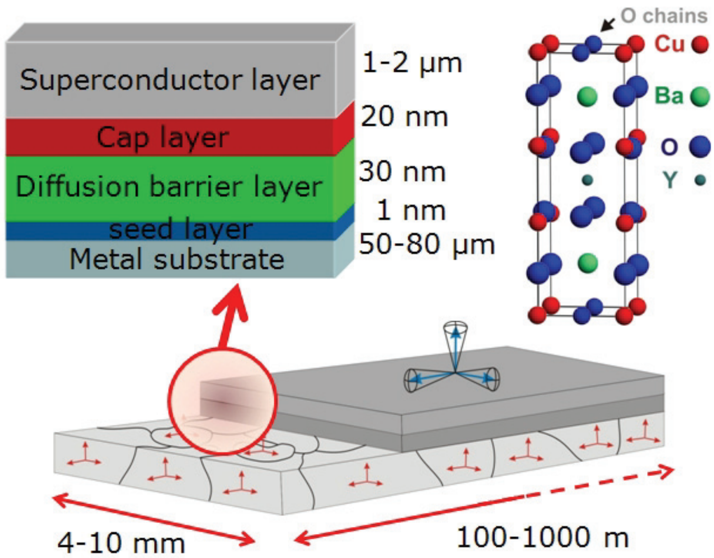

Figure 45 Architecture of the high temperature superconducting coated conductor tape based on $REBa_2Cu_3O_{6+x}$ (RE = Rare Earth & Y).

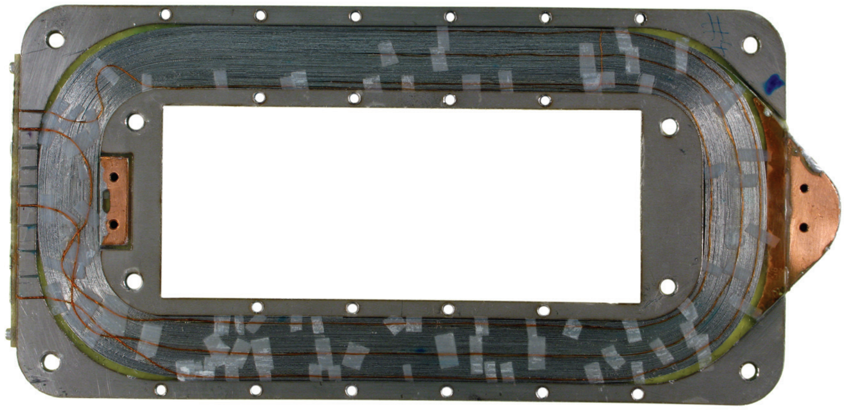

Figure 46 Race track coil holding approximately 32 meters of coated conductor wound around a stainless steel former and outer frame (24 cm x 14 cm x 0.5 cm). Cu blocks are used for current connection and small Cu wires are soldered to the tape providing voltage probes for investigation of the electrical properties of the superconductor [1].

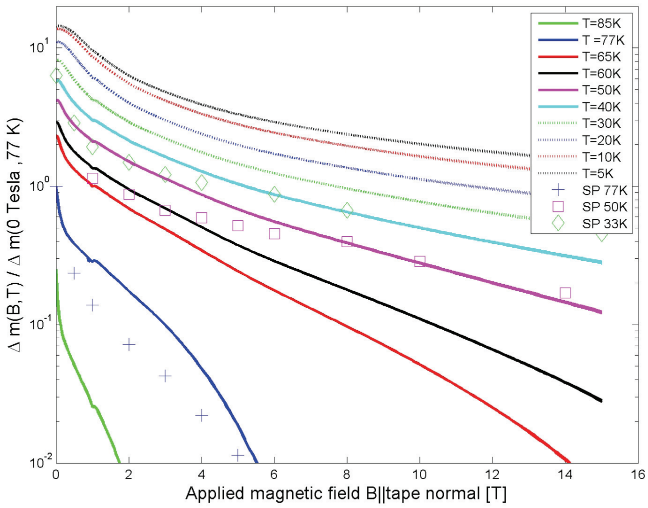

Figure 47 Field and temperature scaling of the hysteresis opening of coated conductor based on Hasteloy substrate and with an I_C = 125 A at T = 77 K [1].

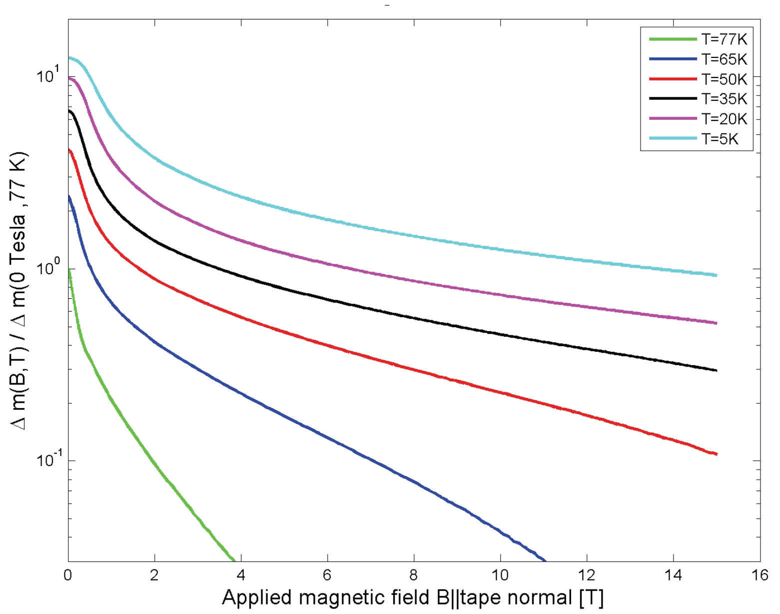

Figure 48 Field and temperature scaling of coated conductor based on Ni-W substrate with a $I_C = 95$ A at T = 77 K [1].

4 Risø DTU contribution to EFDA-TIMES

4.1 Modelling fusion in the energy system

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The target of fusion research during several decades have been that fusion technology will be available for large-scale electricity generation units from about 2050, which means that we cannot expect that nuclear fusion will contribute significantly to global electricity generation until the last quarter of the 21th Century. Fusion units will operate very similar to current large-scale coal-fired or nuclear units that now dominate electricity generation. In the meantime, new technologies – in particular wind and solar – will become significant. However, these technologies are dependent on natural resources located in coastal regions with shallow water or deserts, and they require long-distance transmission to population centres. Another competitor to large-scale thermal units may be small-scale units located at consumers of electricity and heat. Both types of technologies will reduce the market share of large-scale thermal units, which also covers fusion. An additional complexity of the future electricity system is the intermittency of wind and solar resources.

On the other hand, the development of Carbon Capture and Storage (CCS), which is expected in the period until 2050, can be made synergetic to the introduction of fusion power, when it becomes available. In several studies CCS has been identified as an important technology. For CCS the most critical parameter is the loss of thermal efficiency during carbon capture. For example, the electricity efficiency of modern coal-fired steam turbines will be reduced from 46 % to 36 %. It is obvious that a significant part of the thermal loss may be recovered by industry or large district heating systems. However, this opportunity has been widely neglected.

The steam parameters for fusion are similar to advanced coal or combined cycle gas turbines, which is suitable for large-scale combined heat and power (CHP) for urban district heating systems – in contrast to current nuclear fission technology and experience.

In the next decades CCS can be a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Europe, Korea and China, and with large potentials in North America. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used. This may support the penetration of both technologies.

Within the Socio-Economic Research on Fusion (SERF) programme EFDA and the Associations are developing a multi-region global long-term energy modelling framework. The EFDA-TIMES model is a global model divided into 15 regions with the time horizon year 2100. This structure is similar to other global models, which are developed for the International Energy Agency (IEA) and the US Department of Energy. In these models the energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport. Fusion technology is modelled in the Electricity sector in competition with renewables and electricity generating technologies based on fossil fuels or nuclear fission.

The technologies are organised into a network of energy flows linking demand and supply. Forecasts of energy demands in the various sectors come from global economic models. The energy system in these models is optimised by minimising total system costs subject to constraints reflecting infrastructure, technology availability and policy objectives. Most important of the latter is significant reduction of CO_2 and other greenhouse gasses.

The key parameter for fusion is the investment cost per unit of installed capacity. When investment costs are high fusion will enter into the electricity generation mix only in cases of strict CO_2 constraints. Technology learning is likely to lead to lower costs, which may increase the share of fusion by the end of the century, given the assumptions on costs and availability of competing technologies.

In 2010 the main contribution by Risø DTU to the enhancement of the EFDA-TIMES model has been to analyse role of CCS in the various scenarios until 2100 and to introduce a heat distribution infrastructure with few aggregated parameters representing investment cost and network losses. This issue was presented at the semi-annual workshop of the IEA Implementing agreement at Cork, Ireland, November 2010, and a paper “Long-term modelling of Carbon Capture and Storage, Nuclear Fusion, and large-scale District Heating” will be presented at the Risø Internal Conference, May 2011.

1. Grohnheit, P.E. (2010a), Sensitivity Analyses of Biomass and CCS in EFDA-TIMES. Draft Final Report. Socio Economic Research on Fusion. EFDA Technology Workprogramme 2008. WP08-SER-ETM. Activity 2.5.

2. Grohnheit, P.E. (2010b), Modelling CCS, Nuclear Fusion, and large-scale District Heating in EFDA-TIMES and TIAM. Joint UCC-ETSAP Seminar, “Energy Systems Modelling Addressing Energy Security and Climate Change” University of Cork, Ireland, 15-17 November 2010.

5 Industry awareness activities towards ITER

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed and maintained in 2006-2010. The main achievement in 2010 was the successful setting up initiation of the Big Science Secretariat which is described in Section 5.1 below.

The Danish representative of the F4E-ILO network is still Søren B. Korsholm of Association Euratom – Risø DTU. The network now comprises 19 European ILOs. During 2010 the tasks and procurements from the ITER Organisation (IO) and F4E have received more attention from Danish companies, and a number of bids and expression of interests have been placed during 2010 – so far without success. The Danish ILO still announces opportunities for participation in procurements and events to a list of approximately 50 company contact persons.

5.1 The Big Science Secretariat – Denmark

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With offset in the Risø DTU initiative on promoting the ITER industrial opportunities to Danish companies a partnership was made between Risø DTU, FORCE Technology, and Teknologisk Institut (TI) (both are non-profit technology service institutes) with the aim of creating a unit and a project which aims at increasing the Danish industrial involvement in the construction of (European) big science facilities. The project is called Big Science Sekretariatet in 'Danish' or Big Science Secretariat – Denmark (BSS).

Supported by the Confederation of Danish Industry and twelve Danish companies (with sizes in the range 5 to 15.000 employees) the partners applied for funds from the national Council for Technology and Innovation (RTI) and DKK 3.6 million was granted in late 2009. Simultaneously another part of Teknologisk Institut had been granted a similar sum for a related project from RTI and it was requested that the two projects were merged. This was successfully achieved during 2010 and the final signature on the BSS project was made in August 2010. BSS now has a total budget of DKK 11.4 million of which DKK 7.2 million comes from RTI. The time span of the project is until the end of 2012. The project is lead and coordinated by Risø DTU.

The aim of the BSS initiative is two-fold: to increase the awareness of Danish companies on the potential for commercial participation in the construction phase of big science projects, and to assist companies in the required competence and network building phase prior to being able to bid for contracts on ITER, ESS, XFEL, ESO etc. At the same time BSS is connecting to the big science facilities to make the Danish company competences known to them. To facilitate this better BSS is connected to the Danish ILOs of the different organisations – in some cases even carrying the ILO role.

The key point of the BSS project is the BSS secretariat (located at Risø DTU) which is managed by a full time professional. In addition, a number of experts in Risø DTU, FORCE, and TI are connected to BSS, in order to assist Danish companies in their need for competence building and expert advice in the preparation phase. A number of awareness activities will be conducted in 2011, and the project has received positive attention from Danish companies as well as several of the European big science facilities. The project is further described in the BSS web pages www.bigscience.dk.

The BSS project has already received some attention by the Danish press.

1. Association Euratom - Risø National Laboratory, Technical University of Denmark, Annual Progress Report 2006.

6 Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact and assisting students to talks about fusion at different venues. A major part of the activities are the further development and the performances of the Fusion and Plasma Roadshow, described below in Section 6.1. The most important activity of the Fusion and Plasma Roadshow in 2010 was the key participation in the EFDA stand via the Fusion Expo at ESOF in Turin. Two particular public information tasks was conducted in 2010 since Risø DTU was the host for the 10th Annual Public Information Group (PIG) meeting, and in connection to this planned and executed the first PI course for the PI officers of the associations. This was done via an EFDA task and is further described in Section 6.2. Risø DTU and FOM took up the EFDA task of *Interactive Exhibits for the Fusion Expo*. This task is described in Section 6.3.

Over the last couple of years a good contact has been established between Risø DTU and the national science talent center (ScienceTalenter) in Sorø. This resulted in several talks to high school teachers and/or students. However, most importantly, ScienceTalenter has received a grant to make a fusion physics class for 25 science talents from 5 high schools.

For brevity the activities are put in list form below

- Several popular lectures on fusion energy – mainly the roadshow – at high schools and at public science events.
- Assisting students from primary and high school in fusion oriented projects.
- Contact to journalists (web, newspapers, radio and TV) on fusion and ITER related news
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine

6.1 The Danish Fusion and Plasma Road Show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom-Risø National Laboratory, Technical University of Denmark, DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show was funded for three years (2007-2009) by the Danish Research

Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro.

The target audience of the Fusion and Plasma Road Show is primarily high school students. The show is participating in the Danish National Science Festival (September 2010) and in the National Day of Science (April 2010).

In July 2010 the Fusion Road Show formed the key part of the EFDA exhibition at ESOF in Turin, Italy. Two professionals and one support staff from Risø DTU ran the stand in collaboration with EFDA and local staff. The public interest for the exhibits, show and fusion energy in general was very high.

The objective of the road show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people's experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience. The show has its own website: http://roadshow.risoe.dk, where descriptions of the experiments can be found.

In the course of the road show the following experiments are conducted

- An exercise bike connected to a generator and an inverter to be able to supply household appliances with power produced by the bike (New in 2009). This is a very popular experiment, where volunteers in the audience can get a feel for how much we should work to cover our consumption.
- Jacob's Ladder: Plasma created by 10.000 V between two copper wires
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – levitated magnet above superconductor
- Plasma ball lamp

Additional experiments are being developed.

In 2010 the roadshow has been performed seven times in Denmark in its regular form. Five of these were at high schools all over Denmark during the national Danish Science Festival in September 2010. At the National Day of Science in April 2010 the road show participated in a four hour event in Roskilde with an interactive booth. On top of this the road show was presented twice at Sorø Akademi for high school teachers.

The funding for the road show has stopped by the end of 2009. Unfortunately, the rules have been changed and it is currently not possible to apply for funds to this purpose. The road show is quite popular, and we have a waiting list of several high schools who wants to book the show. We are still trying to find ways to fund the road show in the future.

6.2 10th Annual Public Information Group meeting

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Risø DTU hosted the 10th Annual Public Information Group (PIG) meeting in early May 2010. In connection to this event Risø DTU planned and executed the first PI course for the PI officers of the associations. This was done via the EFDA task WP09-PIN-OPIC.

The objective of the task was to facilitate an improvement of the expertise on specific Public Information related areas in the Associations. The objective was meant to be obtained by organizing a day-long seminar for the members of the Public Information Group where acknowledged representatives of the communication profession would train the participants on different fields of Public Information work.

As a first step, the PI Group was monitored (in collaboration with EFDA) to identify the needs of the members. On the basis of the answers it was concluded that majority of them would like to learn more on “how to work with the press” – in a rather broad sense. Therefore, the topic of the PI course to be organised was focusing on media training.

A number of potential media professional educators and trainers were identified and six requests for quotes on executing the course were sent out. Four quotes were received and the company Think-Lab (in collaboration with ESConet) was chosen.

The course was given in a professional way and engaged the participants with several practical exercises as well as through instructive and interesting presentations. 20 participants took part in the event. Informal discussions with the participants after the course gave the impression that they were satisfied with the event and that they had received information which would be useful for their future engagement with the media.

The plan and execution of the task is further described in the Final Report for the task which has been delivered and accepted by EFDA.

6.3 Interactive Exhibits for the Fusion Expo

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FOM and Risø DTU jointly took up the EFDA task “Creating interactive exhibits for Fusion Expo”. The aim of the task is to create new and more interactive exhibits for the Fusion Expo within a number of categories. It is a multistep task, where inspiration and ideas were explored and discussed. This included joint visits to the science theme park Danfoss Universe and the science museum Experimentarium, both in Denmark.

A range of ideas have been developed and prioritized, and the high priority ideas have been described in greater detail. Contacts to a number of potential manufacturers are established, and some of the exhibits have already been created. The task is well on the way, but has not yet been concluded.

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on development of energy technologies and systems with minimal effect on climate, and contributes to innovation, education and policy. Risø has large experimental facilities and interdisciplinary research environments, and includes the national centre for nuclear technologies.

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